

**Water Resources Research Center
Annual Technical Report
FY 2010**

Introduction

Among the problems driven by global climate change, none is more important for long-term sustainability than the potential impacts on water resources. Water is essential for sustaining life and economies. Closely following and deeply intertwined with the need for water is the need for secure and sustainable energy resources and the efficient use of available energy.

Scientists at the University of Hawaii at Manoa (UHM) Water Resources Research Center (WRRC) address those water- and energy-related issues in common with other United States locales and those specific to the islands of the State of Hawaii.

UHM WRRC serves as the focal point for organizing UHM faculty expertise to study the adequacy, integrity, and purity of Hawaii's offshore recreational waters and onshore potable-water resources. WRRC researchers address issues regarding efficient water usage, enhancing groundwater availability, efficient wastewater management and re-use, and related energy-efficiency concerns. Going beyond various monitoring studies, WRRC projects continue to push forward the frontiers of scientific knowledge on island hydrology, generate watershed-assessment and watershed-improvement plans, advance knowledge of energy-efficient desalination and other water-treatment processes, connect hydrologic and economic models of aquifer exploitation, and search for improved indicators of water quality, among other efforts.

The island of Oahu, more specifically the City and County of Honolulu, is truly the "canary in the coal mine" for many water- and energy-related issues that may face the population centers in the U.S. and the world.

Water shortages and energy crises are even more critical to the infrastructure of the Hawaiian Islands because of its geographic isolation and small land area. Therefore, the islands can serve as a microcosm of what may already be a reality for a third of the population in the western and/or southwestern U.S.—limited water shortage. Also, while water-pollution issues are an increasingly recognized problem, the energy crises has also been escalating over the last decade throughout the U.S.

The grants provided through the USGS Water Resources Research Institute Program sets the foundation upon which other activities of the UHM WRRC are structured.

Research Program Introduction

The Hawaii NIWR program for FY 2010 funded five new research projects and allocated a small amount for technology transfer and administration. The new research projects are:

The Determination of the Relationship Between Biodiversity and the Trophic State of Wahiawa Reservoir, Phase II.

Continuing work begun in the FY2008 budget cycle, Professor Clark Liu and Assistant Professor Tao Yan (Civil & Environmental Engineering Department) examined the relationship between biodiversity and trophic status, using a small reservoir on Oahu as a case study. To avoid expensive remediation of occasional eutrophication problems, Liu and Yan devised methods to rapidly assess the trophic status of the reservoir.

Cleaning Up Oahu's Coastal Waters; the Role of Tube-Building Polychaetes in Sediment Dynamics.

Oahu's coastal waters are an important element of the state's major industry-tourism-as well as a source of recreation for the local population and a significant fishery resource. However, the protected coral reefs are threatened by the accumulation of sediments. This study, headed by Zoology Professor Julie Bailey-Brock, examined the fauna associated with algae and tube building polychaete worms, the presence of native and introduced species, grain size composition of sediments, and the rate of accumulation of sediments.

A Decision Support Tool for Managing the Pipe Network of the Honolulu Board of Water Supply (Year 2).

Similar to numerous other cities, Honolulu's municipal water systems has many aging and unreliable components. The Board of Water Supply contends with a number of water main breaks and leaks, and recognizes the need to replace the aging pipelines. Associate Professor V. Amarjit Singh, with Professor Chittaranjan Ray, of the UH Civil and Environmental Engineering Department, continued their work to develop a model to forecast water main breaks and construct an asset management paradigm to rationalize the planning of the water infrastructure work.

Measuring Soil Water Content and Electrical Conductivity Under High Salinity Conditions Using a Novel TDR Method.

Salt accumulation from irrigation is a significant and growing problem on many agricultural lands. The efficient operation of an irrigation system relies on, among other factors, the correct reading of soil water content, which is currently an imperfect process especially in high-salinity soils. WRRRC Research Associate Dr. Xiufu Shuai worked on the development of a new approach to measure water content based on the time domain reflectometry processes.

Hydraulic Properties of the Northern Guam Lens Aquifer System, Territory of Guam, USA.

The objective of this study, conducted by Dr. Aly El-Kadi (Department of Geology and Geophysics), was to estimate the aquifer properties of the Northern Guam aquifer in preparation for the expected increase in water demand. The population on the island is expected to increase dramatically as the result of the proposed military buildup, with as many as 70,000 residents added to the current estimate of about 171,000 residents. The Northern Guam Lens aquifer system is the most important aquifer on the island and currently supplies about 40 mgd of fresh groundwater, mainly for supply to the public. The groundwater demand from the aquifer system is expected to increase proportionally with the additional population.

The technology-transfer project organizes conferences, meetings, workshops, and biweekly seminars; produces newsletters; produces posters and other materials for presentations; and maintains the WRRRC website.

A similar small percentage of WRRIP funding went to the administration program, primarily supporting faculty travel. This is a critically important function given Hawaii's isolated location.

Research Program Introduction

WRRC researchers also continued, under no-cost extensions, five projects begun with previous years' appropriations:

- Experimental Study of Humidification-Dehumidification (HDH) Seawater Desalination Driven by Solar Energy,
- Application of Radar Imagery as Input to a Rainfall-Runoff Model for the Kawela Watershed, Molokai,
- Assessing the Influence of Land-Based Discharges (Streams, Storm Drain, and Groundwater) on the Concentrations and Ratio of Four Human Pathogenic Marine *Vibrio* spp. in Four Categories of Coastal Water Environments of Hawaii,
- Optimal Groundwater Extraction and Water Recycling, and
- Numerical Simulation of the Effects of Borehole Flow on Measured Vertical Salinity Profiles from Deep Monitor Wells, Pearl Harbor Aquifer, Oahu, Hawaii

Experimental Study of Humidification-Dehumidification (HDH) Seawater Desalination Driven by Solar Energy

Basic Information

Title:	Experimental Study of Humidification-Dehumidification (HDH) Seawater Desalination Driven by Solar Energy
Project Number:	2008HI231B
Start Date:	3/1/2008
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	Hawaii 1st
Research Category:	Engineering
Focus Category:	Water Supply, Treatment, None
Descriptors:	Freshwater Supply, Seawater Desalination, Humidification-Dehumidification
Principal Investigators:	Weilin Qu

Publication

1. McGivern, R., 2010, "Humidification-Dehumidification Seawater Desalination System Driven by Solar Energy," MS Thesis, Department of Mechanical Engineering, College of Engineering, University of Hawaii at Manoa, Honolulu, HI, 115 p.

Problem and Research Objectives

Desalination produces freshwater by removing dissolved minerals from seawater. The process has a long history as an effective means to meet agricultural, domestic, and industrial freshwater needs in coastal areas. Technologically mature conventional desalination processes that have been widely used to produce freshwater at industrial-scale include multi-effect distillation, multi-stage flashing, and reverse osmosis.

Multi-effect distillation and multi-stage flashing are based on liquid-vapor phase-change processes where seawater evaporates to water vapor either at atmospheric pressure by adding heat (multi-effect distillation) or at greatly reduced pressure by lowering water's boiling point (multi-stage flashing). This water vapor then condenses to yield freshwater—leaving any previously dissolved minerals as waste byproducts.

Reverse osmosis, alternatively, is based on membrane technology. Using a high-pressure pump, seawater is forced to flow through a membrane. The membrane only allows freshwater to pass while filtering out the dissolved minerals. Freshwater is produced as a result of this filtering with any previously dissolved minerals retained on the input side of the filter.

The primary restriction on the use of conventional multi-effect distillation, multi-stage flashing, and reverse-osmosis technologies is that they are highly energy intensive. The cost of freshwater produced by these three desalination technologies is directly dependent upon the cost of energy, primarily electricity and/or high-grade (high-temperature) thermal energy. While these technologies may be considered cost-effective in regions, such as the Middle East, having abundant and economical local petrochemical energy supplies they are not well suited to regions such as Hawaii because of the high energy cost. The primary energy source used in Hawaii has long been unrefined oil shipped in from Southeast Asia.

Additionally, these three conventional technologies operate under specialized temperature or pressure conditions, e.g., multi-effect distillation requires working temperatures above 100°C, multi-stage flashing requires greatly reduced pressures, and reverse osmosis requires high initial flow pressures and produces a significant reduction of these flow pressures. All of these technological requirements lead to high infrastructure and operating costs.

In contrast, humidification-dehumidification (HDH) seawater desalination represents a relatively new desalination method based on heat and mass-transfer processes. Normal atmospheric air is employed as the medium to convert seawater to freshwater. HDH seawater desalination involves two processes. Seawater is first converted to water vapor by evaporation into dry air in an evaporator (humidification). This water vapor is then condensed out from the air in a condenser to produce freshwater (dehumidification).

HDH seawater desalination operates under more moderate working temperatures (<80°C) and near-ambient system pressures and requires only moderate flow pressures. Given these more moderate system specifications, low-cost materials such as conventional plastics may be used for system construction. These relatively easy-to-achieve construction requirements are expected to lead to a lower infrastructure cost.

Because of the more moderate operating-temperature requirement, HDH seawater desalination can easily be driven by sustainable solar energy. This makes HDH seawater desalination particularly attractive to Hawaii. While its geographical location makes electricity and high-grade petrochemical-based thermal energy expensive in Hawaii, there is abundant solar radiation throughout the islands.

Several literature studies are available that explore HDH as an effective means for seawater desalination. The early work includes those by Bourouni et al. (2001), Al-Hallaj et al. (1998), Assouad and Lavan (1988), Muller-Holst et al. (1999), Abdel-Salam et al. (1993), Xiong et al. (2005a), Shaobo et al. (2005), Xiong et al. (2005b), El-Dessouky (1989), Goosen et al. (2003), and Al-Hallaj and Selman (2002). In these studies conventional shell-and-tube heat exchangers were used as condensers for the dehumidification process. Film condensation over tubes is extremely inefficient as the process involves condensing water vapor out of a mixture of air and water vapor. The presence of air adversely affects the access of water vapor to the cold tube surface.

Klausner and co-workers at the University of Florida described (Klausner et al. 2004, Klausner et al. 2006, Li et al. 2006a, Li et al. 2006b) an innovative diffusion-driven desalination technology to overcome the aforementioned shortcoming. To enhance the condensation in the presence of air, a direct-contact condenser was used in diffusion-driven desalination. The diffusion-driven desalination was powered by waste heat derived from low-pressure condensing steam from a power plant and is viable for industrial-scale freshwater production.

Practical implementation of solar-energy-driven HDH seawater desalination systems requires a fundamental understanding of thermal/fluid transport phenomena in virtually all system components. Our research team launched a research program to establish such a knowledge base through combined theoretical modeling and experimental study. The project supported by the extension of the 2008 U.S. Geological Survey State Water Resources Research Institute Program (WRRIP 2008) constitutes the Phase II of the research program. The focus of the Phase II research is on developing a laboratory-scale experimental system to study parametric trends of the freshwater-production rate.

Methodology

Figure 1 shows a schematic diagram of the laboratory-scale experimental system designed and constructed in our research lab. The system is composed of three main fluid-circulation lines identified in Figure 1 as saltwater, air/vapor, and freshwater.

In the saltwater line an insulated tank stores the saltwater. Heat generated by five 1000-W electrical cartridge heaters installed in the tank, used in the experimental system to simulate solar-energy input, raises the saltwater temperature. A centrifugal pump transports the heated saltwater to an evaporator. The heated saltwater is sprayed through a nozzle into the top of the evaporator so that it comes into direct contact with ambient-moisture air being pumped into the bottom of the evaporator. A portion of the heated saltwater evaporates and thus humidifies the

ambient air. Any saltwater not evaporated collects at the bottom of the evaporator and is returned to the insulated storage tank as high-salt brine.

In the air/vapor line ambient air is pumped, using a forced-draft blower, into the the bottom of the evaporator where it rises and comes into direct contact with the heated saltwater being sprayed into the top of the evaporator chamber. Direct contact with the heated saltwater humidifies the ambient air. The now-humidified air is drawn out of the evaporator chamber and pumped into a condenser. In the condenser chamber the now-humidified air comes into direct contact with cold, working, freshwater being sprayed into the top of the condenser. From the humid air salt-free water vapor now condenses into liquid water and mixes into the working freshwater. The lowered-humidity air remaining after the condensation process is ejected into the external ambient air as exhaust.

In the freshwater line a storage tank holds a fixed amount (limited by the presence of a drain in the sidewall of the tank) of working freshwater. This water is circulated using a centrifugal pump. Before entering the condenser the freshwater is cooled in a chiller to lower its temperature. Additional freshwater captured through the condensation process, in excess of the storage tank's fixed limit of working water, is the newly desalinated water and flows through the storage-tank's drain into a collecting tank.

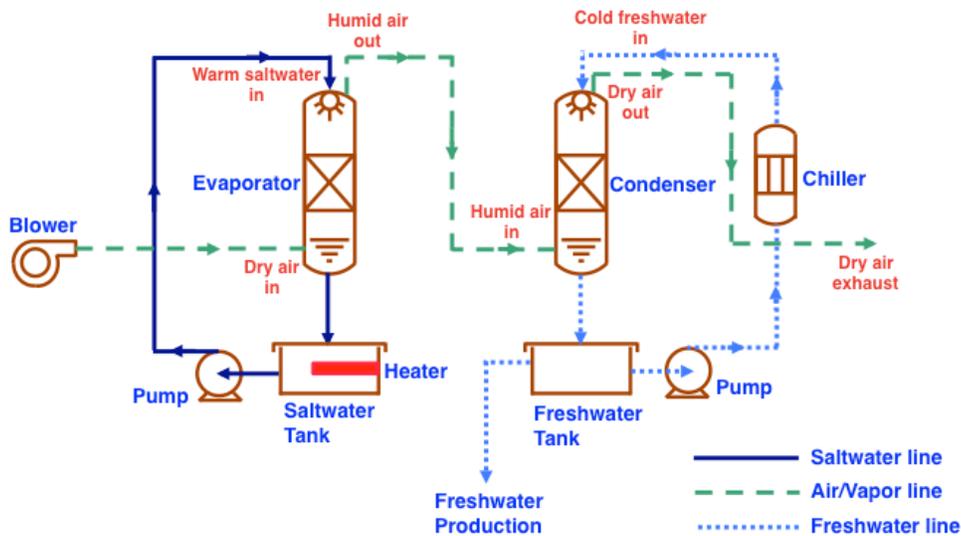


Figure 1. Schematic diagram of HDH desalination lab-scale experimental system.

Figure 2 shows a picture of the experimental system. The evaporator and condenser chambers are shown in the center of the picture. Both are wrapped with black polyethylene foam insulation to prevent heat transfer to or from the ambient environment. The air and water piping is also covered with the same insulation.



Figure 2. Picture of HDH desalination lab-scale experimental system.

To measure the various thermal/fluid parameters during testing the experimental system is fully instrumented. Thermocouples installed at both the inlets and outlets of the evaporator and condenser measure the corresponding inlet and outlet temperatures of air and water. A computer-based data-acquisition system automatically records the thermocouple readings. Saltwater and freshwater flow rates are measured using two rotameters. Air velocity in the pipe upstream of the evaporator is measured using a hot-wire thermo-anemometer. Heating power of the cartridge heaters is measured using a precision power meter. Freshwater production is determined by collecting the freshwater overflow through the storage-tank's drain for a period of time and dividing the volume of the collected water by the time period.

In use the components of the experimental system are first set to the desired testing constraints. The system is then allowed to reach a steady state where thermal and fluid-flow parameters no longer vary with time. Once the entire system has reached a steady state, readings are computer recorded at 5-second intervals from the thermocouples for, depending on freshwater-production rates, 20 to 40 minutes. Readings from the anemometer, power meter, and rotameters are manually recorded. During the steady-state measurement period freshwater production is collected and, at the conclusion of the test period, its volume is measured and recorded.

Principal Findings and Significance

This experimental study focuses on parametric trends in the freshwater-production rate, i.e., how the production rate of freshwater is affected by changes in the various thermal/fluid parameters. We are particularly interested in how the freshwater-production rate is affected by the heat input to the saltwater held in the storage tank.

Experimental results from this study are summarized in Figure 3 which plots the freshwater-production rate, in gallons per hour (GPH), as a function of the heater power (in kW) input to the saltwater. Three heating-power input levels are tested: 2.65, 3.60, and 4.45 kW.

Flow rate of the heated saltwater is fixed at 2 gallons per minute (GPM) and flow rate of the cooled freshwater is fixed at 1.5 GPM. Temperatures of the saltwater at the inlet of the evaporator are 51°C for 2.65 kW of heater power, 55.5°C for 3.6 kW, and 59°C for 4.45 kW. Temperatures of the cooled freshwater at the inlet of the condenser range from 17.5°C to 19.5°C, increasing only slightly with increased heater power. Air velocity has a fixed value of about 6.2 m/s.

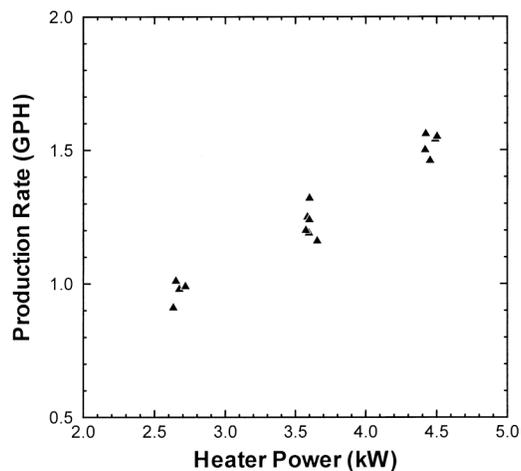


Figure 3. Experimental freshwater-production rate vs. heater-power input to the saltwater.

Figure 3 shows that the freshwater-production rate increases with increasing heater-power input. This implies that increased solar-radiation capture will lead to higher freshwater-production rates in actual solar-energy-driven desalination systems. Figure 3 further reveals that the relationship between the freshwater-production rate and the heater-power input is fairly linear. To explore the freshwater-production rate per unit of power input the ratio of the freshwater-production rate to the heater-power input is plotted in Figure 4 as a function of the heater-power input. The ratio is fairly constant with an average value of 0.348 GPH/kW, which means that for 1 kW of heating-power input the present experimental system is able to produce 0.348 gallon of freshwater per 1 hour. This production rate to power value is only taking into consideration the heating power. The necessary cooling power is not factored into the calculation. In addition, the thermal energy removed during the condensation process was not recovered in the study. It is expected that the freshwater-production rate per unit input heating power will increase if energy recovery technologies are applied.

Comparing this average production rate to other conventional electrical devices such as water distillers, we found congruency between the device and the HDH system. A typical 600 W electric distiller can produce 1 gallon of water in 5 hours. This translates to 0.333 GPH/kW which is roughly equal to what the HDH system can produce. From an energy standpoint this

is expected. However, the advantage of the HDH system is that it can be operated from lower grade energy and industrial waste heat.

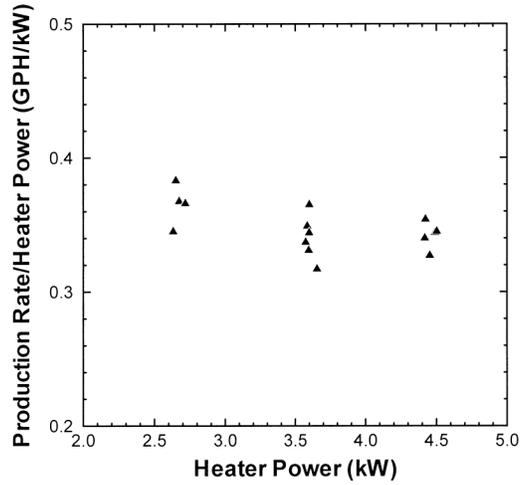


Figure 4. Ratio of freshwater-production rate to heating-power input vs. heater-power input.

The Oahu solar map is examined to explore the estimated freshwater-production rates if the present lab-scale experimental system is operated outdoors and driven by solar energy. The result is shown in Figure 5. The Ewa plain on the west side of Oahu, Hawaii, is selected as the site of study due to its potential freshwater shortage and expected population growth. Figure 5 shows that with 1 square meter of land on the Ewa plain used for solar-energy collection the present experimental system is able to produce 2.02 gallons of freshwater per day.

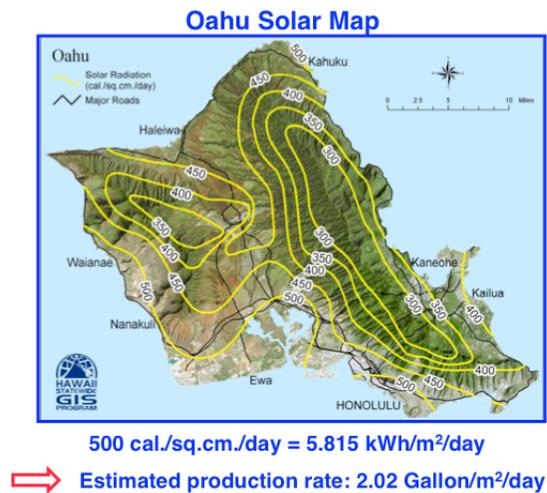


Figure 5. Oahu’s solar map illustrates the estimated freshwater-production rate and the Ewa plain study area.

The present experimental study also reveals that while the freshwater-production rate decreases slightly with decreasing air velocity it is not sensitive to variations in the saltwater and freshwater flow rates. Doubling the saltwater or freshwater flow rate does not create a substantial change in freshwater production.

The experimental results also show very low water production sensitivity toward air flow rate. The difference in water production between different air flow rates is very miniscule and inclusive. After considering variation and system error, these results are inclusive but demonstrate the weak correlation between the water production and air flow rate.

In summary, a HDH seawater desalination lab-scale experimental system is designed, constructed, and tested to prove the concept of the desalination technique. The testing system is able to deliver stable and highly repeatable freshwater production for long-term operations. Results from testing runs indicate that among the many operating parameters the system performance is most affected by the heat input to the saltwater. The knowledge we gained through this project can readily be applied towards developing industrial-scale HDH desalination systems.

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Notable Awards and Achievements

Our solar-energy-driven HDH seawater desalination research program recently received \$48,000 in funding from Hawaii Technology Development Venture (HTDV) to support a research and development project entitled "Solar Energy Driven Humidification-Dehumidification Seawater Desalination Systems." The project ran from 1 April 2009 to 31 December 2009. Our research team collaborated with Sopogy, a Hawaii based solar technology company, to design, construct, and test a laboratory-scale prototype HDH desalination system.

Award No. 08HQAG0142 Application of Radar Imagery as Input to a Rainfall-Runoff Model for the Kawela Watershed, Molokai

Basic Information

Title:	Award No. 08HQAG0142 Application of Radar Imagery as Input to a Rainfall-Runoff Model for the Kawela Watershed, Molokai
Project Number:	2008HI282S
Start Date:	9/1/2008
End Date:	12/31/2010
Funding Source:	Supplemental
Congressional District:	Hawaii 1st
Research Category:	Climate and Hydrologic Processes
Focus Category:	Surface Water, Hydrology, Groundwater
Descriptors:	Radar-Raingage Rainfall, Rainfall-Runoff Model, Groundwater Recharge
Principal Investigators:	Aly I El-Kadi

Publications

There are no publications.

Introduction

Watershed-scale studies in Hawaii frequently require the integration of multiple aspects of basin-hydrology data including groundwater recharge, pollutant transport, sediment discharge, streambed erosion, and streamflow. Additionally the effects of rainfall variation or land-cover changes on any of these aspects may need to be assessed. As described by Field et al. (2007) for the Hanalei watershed, Kauai, multi-disciplinary analysis of terrestrial and marine ecosystems provides a broader understanding of the processes within a watershed. Multi-disciplinary analysis is particularly useful for watershed managers facing multiple concerns of improving coastal water quality, maintaining sustainable water supply, and restoring ecological integrity.

The primary factors controlling hydrologic processes in Hawaii watersheds are the temporal and spatial distribution of rainfall and runoff/infiltration characteristics. Existing watershed modeling studies in Hawaii include those on the Manoa-Palolo Stream, Oahu by Sahoo et al. (2006) and by El-Kadi and Yamashita (2007), on the Makaha Valley, Oahu (Mair et al. 2007), and on the Hanalei watershed, Kauai (Polyakov et al. 2007). Steep/mountainous terrain generates substantial and powerful runoff and streamflow is highly variable, often producing high peak flows in streams that have low base flows (Oki 2004). Rainfall in Hawaii is characterized by steep spatial gradients (Giambelluca et al. 1986). Existing networks of raingages are usually too sparse to reflect the full spatial variability of basin-scale areas. In this type of topography, time-series rainfall maps are generally more useful in identifying rainfall patterns than interpolation between the few existing raingages.

The National Weather Service's Weather Surveillance Radar-1988 Doppler Next Generation Weather Radar (NEXRAD) provides radar-inferred precipitation images (Smith and Krajewski 2002). Studies (e.g., Xie et al. 2006, Wang et al. 2008) have correlated these NEXRAD images with raingage data. The rainfall maps were made available in the form of Geographic Information System- (GIS-) coverages (Gorokhovich and Villarini 2005, Xie et al. 2005). Such maps have been used as input for rainfall-runoff modeling in flat terrain (Peters and Easton 1997), complex mountainous terrain (Yates et al. 2000), and urban watersheds (Smith et al. 2007). Kalinga and Gan (2006) show that simulations with NEXRAD data accurately predict runoff hydrographs for convective storms but are less accurate for stratified storms. NEXRAD images for Hawaii are available with a spatial resolution of ~1 km every 6 minutes from 2001 to the present day. However the applicability of these images for Hawaii for use in hydrologic modeling has yet to be tested.

The Kawela watershed, a medium-size watershed on Molokai covering an area of 13.7 km², may provide a valuable and valid testing location. Average annual rainfall across the Kawela watershed is ca. 1 m. Annual rainfall changes gradually from ca. 3 m at the top of the ridge to ca. 0.5 m at the coast. Rainfall maps can be used to generate a rainfall-runoff model for the Kawela watershed to evaluate the accuracy of such a model for various climate and land-cover scenarios. The geographic/geologic/topographic patterns of the Kawela watershed are similar to those of many leeward Koolau watersheds on Oahu and similar areas on other Hawaiian islands. Therefore a successful demonstration of this form of hydrologic modeling for the Kawela watershed would indicate applicability of this approach to other watersheds.

The Kawela watershed is also a promising study site because it is already being studied in a multi-disciplinary ridge-to-reef investigation by the U.S. Geological Survey. Erosion rates, land-use change, vegetation in the watershed, and sediment dynamics in the reef flats have been or are currently being assessed. Having already demonstrated cooperation with research studies, local stakeholders may be expected to be open to accepting additional research activities.

Problem and Research Objectives

The objective of this study is to compare radar-inferred rainfall with observed rainfall from raingages on Molokai, identify applicability of radar rainfall for the Kawela watershed, and provide a combination of radar- and gage-rainfall maps as input to a rainfall-runoff model for the Kawela watershed, Molokai. The rainfall-runoff model will be developed in a subsequent study to evaluate the accuracy of such a model for various climate and land-cover scenarios on streamflow and groundwater recharge.

Methodology

The project will be addressed in three phases: 1) compare radar-inferred rainfall with observed rainfall from raingages on Molokai, 2) identify applicability of radar rainfall for the Kawela watershed, and 3) provide a combination of radar- and gage-rainfall maps as input to a rainfall-runoff model for the Kawela watershed. Results will be published in a scientific journal.

Radar-gage comparison—The first challenge is to convert the extensive NEXRAD image dataset to a spatial grid of rainfall intensities covering Molokai, which may then be transferred as a cumulative function to spatial hourly and daily rainfall values. For the period of existing radar data, 15 raingages have precipitation records available. Of these raingages, 12 have hourly or smaller temporal sample intervals. The raingage rainfall can be compared to the radar-inferred rainfall for hourly and daily records.

Radar-rainfall in Kawela—The radar-inferred precipitation will be verified by correlation with existing raingages in and near the Kawela watershed. Such correlation serves to validate the radar-inferred precipitation image data. Bias and scaling factors from individual raingages can be assessed to improve the radar data.

Rainfall map for Kawela—Using the results from the comparison, rainfall maps will be generated by integrating radar-inferred and raingage rainfall. A subsequent study will utilize the maps as input to a rainfall-runoff model for the Kawela watershed, Molokai.

Principal Findings and Significance

Progress to date includes the collection and processing of radar-rainfall and raingage rainfall data for the comparison.

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Assessing the Influence of Land-Based Discharges (Streams, Storm Drain, and Groundwater) on the Concentrations and Ratio of Four Human Pathogenic Marine Vibrio spp. in Four Categories of Coastal Water Environments of Hawaii

Basic Information

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Principal Investigators:	Roger Fujioka

Publications

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Introduction

The majority of the available information concerning *Vibrio* species (spp.) is based on studies conducted in temperate regions. Information on the prevalence and ecology of these species in tropical areas, such as Hawaii, is limited. Four pathogenic *Vibrio* spp. (*V. alginolyticus*, *V. cholerae*, *V. parahaemolyticus*, *V. vulnificus*) have been documented to cause human infections in Hawaii. *V. vulnificus* infections have recently resulted in two deaths related to exposure to Hawaii's coastal waters. One death occurred on the island of Hawaii and the second death occurred on Oahu (Wilson 2006). Over the past 20 years, four isolated cases of *V. cholerae* infections were confirmed on Oahu in individuals that did not travel outside the state (Leidemann 2005). The source of these infections could not be determined, and contaminated seafood was considered to be the most likely source. In addition, infections of *V. parahaemolyticus* associated with undercooked crabs (Barker 1974) and *V. alginolyticus* infections in surfers with cuts have also occurred in Hawaii (Blake et al. 1980). Prior to the present study there have been no studies conducted to determine the prevalence of these pathogens in the coastal waters of Hawaii. Thus, the major goal of this study was to obtain data concerning the prevalence of pathogenic *Vibrio* spp. in Hawaii's coastal waters and to determine their potential public health significance to individuals who use these waters for recreational purposes.

Problems and Research Objectives

Current Problems Concerning *Vibrio* spp. Enumeration in Coastal Waters

Several problems have been identified in assessing issues related to *Vibrio* spp.:

1. None of the existing methods to enumerate *Vibrio* spp. from water samples have been approved by the United States Environmental Protection Agency. Thus, there is a need to collect additional data and to identify an appropriate enumeration method.
2. No systematic studies exist to determine concentrations of pathogenic *Vibrio* spp. in various types of Hawaiian coastal waters used by humans.
3. Concern of human exposure to *Vibrio* spp. has been raised—testing for exposure to *Vibrio* spp. in recreational coastal waters cannot proceed until environmental data are collected and measurement methods are approved. Thus, data gathered from this study will provide the first step in determining the potential risk from *Vibrio* spp. at various Hawaiian coastal water sites.

The principal objectives of this proposal are to:

1. To determine the prevalence of the four human pathogenic *Vibrio* spp. (*V. alginolyticus*, *V. cholerae*, *V. parahaemolyticus*, *V. vulnificus*) in coastal waters approved for recreational use which are characterized by negligible to varying degrees of land-based runoff.
2. To determine the prevalence of the four human pathogenic *Vibrio* spp. in confined coastal waters, which are not approved for recreational use and are characterized by high degrees of contamination from land-based runoff.

3. To determine if conditions of low salinity and warm water temperature ($>30^{\circ}\text{C}$), which characterize some coastal water sites on the island of Hawaii, are selective for the growth of the four human pathogenic *Vibrio* spp.
4. To determine the prevalence of the four human pathogenic *Vibrio* spp. in sediments of coastal waters as a possible source of these pathogens into the water column.
5. To determine whether raw sewage and various treatments of sewage (primary, secondary and disinfected) that are discharged into Hawaiian coastal waters, are possible sources for the four human pathogenic *Vibrio* spp.

Methodology

Sample Categories

Sampling sites on the islands of Oahu and Hawaii were divided into four water-quality categories based on their use and the degree of impact by land-based runoff.

1. Primary Coastal Beaches Approved for Swimming (Oahu): these sites consist of the more popular beaches on Oahu and are characterized by no obvious impact by land-based runoff. Thus, waters at these sites are generally characterized as having high salinity and low turbidity.
2. Secondary Coastal Beaches Approved for Swimming (Oahu): these sites consist of less popular beaches on Oahu and are characterized by variable impact by nearby land-based runoff. Thus, waters at these sites are generally characterized as having lower salinity and higher turbidity than waters at primary coastal beaches.
3. Coastal Harbors, Ponds, and Canals Not Approved for Swimming (Oahu): these sites are confined coastal bodies that have poor circulation with the open ocean. They are highly susceptible to land-based runoff and, as a result, have variable salinities with high turbidity. Because these sites are contaminated with land-based runoff, they are not approved for primary contact recreational use. However, human activity and exposure to these waters are acknowledged to occur. The prime example of this type of site is the Ala Wai Canal where a documented case of accidental human contact with water at this site, resulted in infection and death by *V. vulnificus*.
4. Approved Swimming Sites (Island of Hawaii): these study sites were selected based on past evidence of *V. vulnificus* wound infections. While beaches on Oahu are largely represented by sandy swimming beaches, the beaches on the island of Hawaii are characterized by a rocky coastline because the island is geologically younger than Oahu. Coastal water sites used for recreation on the island of Hawaii are often large rock-enclosed coastal ponds. Many of these sites are impacted by land-based runoff, generally susceptible to freshwater input and are characterized by low and variable salinity.

The distinctions between coastal waters on the islands of Hawaii and Oahu are related to the geological ages of lava that formed the two islands, and the corresponding weathering effects on the lava rock formation at coastal water sites. In this regard, Oahu is 2–3 million years old whereas the island of Hawaii is less than 1 million years old (and still forming). Age and weathering controls the hydrogeology of each island, and over time, sedimentary deposits form

a relatively impermeable rock called caprock. This caprock is prevalent on Oahu while not on the island of Hawaii. As a result, when it rains on Oahu, the caprock prevents groundwater from flowing out into the coastal waters and forces it to percolate underground. On the island of Hawaii however, the absence of caprock causes the groundwater to be readily discharged into coastal waters and ponds. This leads to ponds with low salinity waters which is a condition known to be conducive for the growth of bacteria such as pathogenic *Vibrio* spp. Some of these low salinity coastal ponds are also characterized by high water temperature generated by the discharge of lava-heated groundwater into coastal areas. Some of these thermal ponds have previously been identified as sources for the transmission of *V. vulnificus* to humans. A case of a person swimming in a thermal pond, becoming infected and dying from *V. vulnificus* has been documented.

Sample Collection

At all primary and secondary recreational beaches, water samples were collected (in sterile, one-liter plastic sampling bottles) in waist deep water. Harbor, canal, and pond sites were sampled from shore using a sampling bucket and were then similarly collected in sterile one-liter plastic bottles. Sediment samples were taken in knee deep water using a strainer containing a nylon mesh. Three samples were taken from each site, placed into sterile Whirl-Pak bags, and transported to the laboratory for analysis. All Oahu samples were analyzed within three hours of collection.

Water samples from the island of Hawaii were similarly collected into sterile one-liter plastic bottles. Due to transport times to the Oahu laboratory, these samples were processed within eight hours of collection.

Using a sampling pole, sewage samples from the Hawaii Kai, Sand Island, and Wahiawa Wastewater Treatment Plants on Oahu were collected in sterile half-liter plastic bottles and transported to the laboratory. Samples were analyzed within three hours of collection.

All samples were transported for analysis to the Oahu laboratory in a cooler without ice.

Chemical Parameters of Water Samples (Turbidity and Salinity)

Water samples were measured for turbidity and salinity. Turbidity was measured using a Hach Turbidometer and recorded as Nephelometric Turbidity Units. Salinity was measured using a refractometer and recorded as parts per thousand (ppt). Both turbidity and salinity measurements were used to determine whether sites were impacted by freshwater/groundwater discharge.

Bacteriological Analysis of Samples

Water and Sewage Samples

Membrane filtration was used for the enumeration of both total marine bacteria and vibrio bacteria. A peptone buffer (PB) solution containing 0.1% peptone and 3% NaCl (Azanza et al. 1996) was used to dilute samples prior to filtration. Water samples were diluted as needed with sterile PB and 25 ml portions were filtered through a 0.45 μm Gelman filter and placed onto either marine agar (MA), thiosulfate citrate bile salts sucrose (TCBS) agar, or CHROMagar Vibrio (CV) agar. All media was prepared in accordance with manufacturer specifications. Inoculated agar plates were incubated for twenty-four hours at 35°C. After the incubation period, colonies on each plate were counted. Approximately 20% of turquoise colonies, 20% of mauve colonies, and 10% of colorless colonies were picked off CV plates using sterile toothpicks and streaked for isolation on fresh CV plates. Isolated colonies were then streaked onto tryptic soy agar (TSA) + 0.5% NaCl plates for biochemical testing.

Sediment Samples

Bacteria were eluted from sediment samples using a procedure modified from that used by the United States Geological Survey (Myers et al. 2003). Sediment samples were mixed using a sterile wooden spatula and 100 g sub-samples were placed into sterile half-liter plastic bottles. A total of 200 ml of PB was added to each bottle, followed by vigorous hand shaking for five minutes to elute the bacteria from the sediment to the water or supernatant phase. The bottle was then left undisturbed for thirty seconds to allow the sediments to settle. The supernatant was then transferred into a separate sterile bottle. This sediment elution process was done twice and the two supernatants were combined. The combined supernatant samples were processed in a manner similar to that described earlier for the water samples and isolates were picked off the CV plates as described above. A small aliquot (10 g) of each sediment was placed onto a drying dish and dried in a 105°C oven for twenty-four hours to determine the dry weight of the sediment.

Presumptive Identification Using Biochemical Testing

Presumptive human pathogenic *Vibrio* spp., which formed turquoise, mauve, and colorless colonies on CV plates were picked and streaked for purification on TSA + 0.5% NaCl agar. A twenty-four hour culture of the isolates grown on this medium was used to speciate the colonies based on results of two additional biochemical tests (sucrose fermentation, growth at various levels of salt) following guidelines published by the U.S. Food and Drug Administration Bacterial Analytical Manual and reported by DePaola and Kaysner (2004). To test for sucrose fermentation, isolates from TSA + 0.5% NaCl agar were streaked onto TCBS agar. The formation of yellow colonies after a twenty-four hour incubation period indicated sucrose fermentation. Isolates were also tested for salt tolerance by observing for growth in nutrient broth containing various concentrations of NaCl (0%, 6%, 8%, 10%). Salt tubes were inoculated by homogenizing a single colony from a TSA + 0.5% NaCl plate into a tube of 2%

saline broth and then using 0.1 ml of the homogenate to inoculate each of the (0%, 6%, 8%, and 10%) salt tubes. After incubation at 35°C for seven days the presence (or absence) of growth was documented (Choopun et al. 2002).

Genetic Confirmation of Presumptive Isolates Using Species-Specific PCR Primers

More recently, a new genetic test called PCR has been used to speciate most bacteria. For genetic testing, the DNA of presumptive isolates was extracted according to the method described by Lee et al. (2004). Briefly, isolates were grown overnight at 35°C in 1 ml of tryptose soy broth containing 1.5% NaCl. The culture was then boiled at 100°C on a heat block for five minutes and centrifuged for five minutes at 10,000 RPM in a microcentrifuge (Lee et al. 2004). The supernatant was then used directly for PCR reactions. Species-specific PCR primers used in this study to confirm the identity of *V. cholerae*, *V. parahaemolyticus*, and *V. vulnificus* are listed in Table 1. These primers target specific regions of the DNA of each species. The specific products generated by the use of these primers have corresponding molecular weight, which were visualized as bands on 1.5% agarose gels.

Table 1. Gene targets and references of PCR primers used for confirmation of *V. cholerae*, *V. parahaemolyticus*, and *V. vulnificus* isolates.

Species	Target Gene	Reference
<i>V. cholerae</i>	16S-23S rDNA ISR	Chun et al., 1999
<i>V. parahaemolyticus</i>	pR72H	Lee et al., 1995
<i>V. vulnificus</i>	16S rDNA	Kim and Jeong, 2001

Principal Findings and Significance

1. What is the prevalence of the four human pathogenic *Vibrio* spp. (*V. alginolyticus*, *V. cholerae*, *V. parahaemolyticus*, *V. vulnificus*) at primary coastal beaches on Oahu where the greatest exposure to swimmers occur, and where the water is characterized as having consistently high salinity (35–36 ppt) and negligible impact from land-based runoff?
 - The results showed clear prevalence (100%) of *V. alginolyticus*, the least virulent human pathogenic *Vibrio* sp., and the absence of the three more virulent *Vibrio* spp. (*V. cholerae*, *V. parahaemolyticus*, *V. vulnificus*).
 - The first significance of these findings is that since most people swim at primary recreational beach sites on Oahu, the expected exposure and risk of infection by virulent *Vibrio* spp. (*V. cholerae*, *V. parahaemolyticus*, *V. vulnificus*) is minimal.
 - The second significance of these findings is that good quality coastal waters with high salinity prevent growth and prevalence of highly virulent *Vibrio* spp.
2. What is the prevalence of the four human pathogenic *Vibrio* spp. at secondary recreational beaches on Oahu where less exposure (as compared with primary beaches) to swimmers occur, and where the water is characterized by variable degrees of land-based runoff resulting in variable salinities (6.0–32 ppt)?

- The results showed the primary prevalence of *V. alginolyticus* (100%), and the secondary prevalence of *V. vulnificus* (40%) and *V. parahaemolyticus* (20%), and the absence of *V. cholerae* at these sites.
 - The first significance is that, as with primary swimming beaches, at these secondary sites the least pathogenic *Vibrio* sp., *V. alginolyticus*, is the most predominant.
 - The second significance is that at these same sites, where water salinity is lowered due to land-runoff, the more virulent *Vibrio* spp. (*V. parahaemolyticus*, *V. vulnificus*) were also prevalent. This indicates, in agreement with previous studies, that the prevalence of these two species are highly influenced by water salinity.
 - The third significance is that because relatively few people swim at secondary swimming beaches on Oahu, the expected exposure and risk of infection to most swimmers to the more virulent *Vibrio* spp. (*V. parahaemolyticus*, *V. vulnificus*) is minimal.
3. What is the prevalence of the four human pathogenic *Vibrio* spp. in confined coastal waters such as harbors, canals, and ponds, which are not approved for swimming?
- Coastal water at these sites are consistently contaminated by land-based runoff resulting in salinity ranging from 3 to 35 ppt. Moreover, as these coastal waters are not effectively flushed out by open ocean waters, they are considered unsuitable for swimming. However, primary human contact, including swimming, occasionally occurs at these sites.
 - The results showed the primary prevalence of *V. alginolyticus* (100%), and the secondary prevalence of *V. parahaemolyticus* (40–71%) and *V. vulnificus* (0–57%), and the absence of *V. cholerae*.
 - The significance of these findings is that, as these sites are not designated for swimming, people should not be having direct contact with these waters. In the absence of primary contact exposure, the risk for transmission of *Vibrio* spp. to humans should be negligible. However, if people were to swim at these sites, they would be exposed to three of the four known human pathogenic *Vibrio* spp. (*V. alginolyticus*, *V. parahaemolyticus*, *V. vulnificus*) that were tested for in this study.
4. What is the prevalence of the four human pathogenic *Vibrio* spp. at coastal water sites on the island of Hawaii, which are used for swimming?
- Coastal waters of the island of Hawaii are very diverse and differ from the coastal waters on Oahu. Most coastal water sites on the island of Hawaii are characterized as being contaminated by land-based, sub-surface water discharges and having salinity ranging from 8 to 33 ppt.
 - The results showed primary prevalence (89–100%) of *V. alginolyticus* and the secondary prevalence of *V. parahaemolyticus* (22–50%) and *V. vulnificus* (22–100%) at these sites. 100% prevalence of *V. vulnificus* also occurred in the thermal ponds that were tested, along with the absence of *V. cholerae* from any of the coastal sites.
 - The first significance of these findings is that coastal water sites on the island of Hawaii are designated for swimming but the number of people who use these sites are substantially less than those who use coastal waters on Oahu. However, people who swim in coastal waters on the island of Hawaii appear to be at greater risk of becoming infected

with *V. parahaemolyticus* and *V. vulnificus* than swimmers on Oahu because swimming sites used by the public on the island of Hawaii are mainly comprised of low salinity waters.

- The second significance of these findings is that when the salinity of coastal waters was lowered by land-based runoff and water temperature rose due to sub-surface lava activity, the prevalence of the more virulent *Vibrio* spp. (*V. parahaemolyticus*, *V. vulnificus*) also increased.
5. What is the prevalence of the four human pathogenic *Vibrio* spp. found in the coastal water sediments on the island of Oahu?
- The results showed that the prevalence of pathogenic *Vibrio* spp. in coastal sediments followed a trend similar to the prevalence of such pathogens in coastal beach-water samples. *V. alginolyticus* was prevalent in both primary and secondary beach sediment while *V. parahaemolyticus* and *V. vulnificus* was only prevalent in secondary beach sediment. *V. cholerae* was not recovered from sediment samples.
 - The first significance of these results is that sediments can be seen as a source of human pathogenic *Vibrio* spp. into the water column, and may possibly be the most stable source of the three human pathogenic *Vibrio* spp.
 - The secondary significance is that when swimmers cut themselves from coastal water sediments, they may be exposed to high concentrations of pathogenic *Vibrio* spp.
6. What is the prevalence of the four human pathogenic *Vibrio* spp. in human raw sewage, primary treated, secondary treated and disinfected sewage?
- The results showed that *V. parahaemolyticus* and *V. vulnificus* were sporadically present in raw sewage and in effluent having received primary treatment at all three tested wastewater treatment plants. *V. cholerae*, on the other hand, was consistently recovered from raw sewage and from effluent having received primary treatment at all three tested wastewater treatment plants.
 - The first significance of these results is that some humans are infected with and are shedding the three most virulent *Vibrio* spp. (*V. cholerae*, *V. parahaemolyticus*, *V. vulnificus*) into the sewage system.
 - The second significance is that human sewage is the only known environmental source of *V. cholerae* in Hawaii. The low salinity of wastewater favors growth of *V. cholerae*. Accidental release of raw sewage can introduce these pathogens into coastal waters that may lead to public health consequences for users of such waters.

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Optimal Groundwater Extraction and Water Recycling

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Principal Investigators:	James A. Roumasset

Publications

1. Wada, C.A., 2010, Optimal and Sustainable Groundwater Management: Multiple Aquifers, Watershed Conservation, and Water Recycling, Ph.D. Dissertation, University of Hawaii at Mānoa Department of Economics.
2. Roumasset J.A., K. Burnett, and A.M. Balisacan (eds.), 2010, Sustainability Science for Watershed Landscapes. Singapore: Institute of Southeast Asian Studies; Los Banos, Philippines: Southeast Asian Regional Center for Graduate Study and Research in Agriculture.
3. Roumasset, J.A., and C. Wada, 2010, Beyond Sustainable Yield: Managing Multiple Aquifers, Recycling, and Watershed Conservation in the South Oahu Aquifer System, University of Hawaii at Manoa Water Resources Research Center, Honolulu, Hawaii.

Problem and Research Objectives

Water scarcity has long been an important issue in many regions around the world and the threat of climate change has recently brought it further to the forefront of policy discussions. On Oahu (Hawaii), for example, some experts believe that the island's groundwater resources will be "committed" within the next twenty or thirty years (Wilson Okamoto Corp. 2008). However such studies are based on water-use projections and estimates of sustainable yield that often do not consider efficient demand conservation or improved supply-side management. Management strategies such as expansion of reservoirs, implementation of wastewater recycling, improved conjunctive use of groundwater and surface water, new pricing structures, voluntary or mandatory quantity restrictions, and watershed conservation all serve to slow the onset of groundwater scarcity as demand for water continues to grow.

Analyses in the engineering literature have begun to incorporate a wide range of management instruments, such that a portfolio of demand- and supply-side strategies are chosen in conjunction with groundwater extraction (Jenkins et al. 2001, Draper et al. 2003, Jenkins et al. 2004, Wilkinson and Groves 2006). However these studies do not attempt to solve for the vectors of management instruments that maximize the present value to the users. That task requires the application of public and resource economics.

At the same time little attention has been paid in the resource-economics literature to recycled wastewater and its potential role as an intermediate or sector-specific backstop. Since each demand sector requires a particular quality of water, recycled wastewater can potentially serve as a sector-specific backstop resource. Our research addresses the problem of integrating a water-recycling program with groundwater management in an economic-welfare-maximizing framework. To investigate the principle of optimal groundwater extraction in conjunction with wastewater recycling and seawater desalination in a two-sector (household/potable and non-household/non-potable) framework we develop a dynamic groundwater economics model. For identical satellite treatment facilities around the island, i.e., a constant amortized unit cost of recycled water, we numerically solve the optimization model. The simulation results provide optimal groundwater extraction, wastewater recycling, and seawater desalination quantities in every future period; the trajectories of the aquifer-head level; the optimal implementation of groundwater substitution; and the price paths that would induce efficient groundwater use.

Methodology

The Model

We develop and solve an optimal control model that integrates groundwater extraction, water recycling, and desalination for consumption in two demand sectors. Since water demand is multifaceted, from a long-term perspective, infrastructure choice should match the varying characteristics of water required for different end-users in terms of quantity and quality.

Generally benefits from certain uses may vary by input-water quality so that optimality would not always require obtaining the minimum allowable quality for each use. To keep the model

tractable, however, we aggregate non-potable uses into a single demand category and assume no additional benefit from using a higher quality source than necessary. Groundwater extraction is the primary source of high quality (potable) water. No surface water is available, but lower-quality (non-potable) water can be obtained from recycling wastewater. Desalinated seawater serves as a high-quality backstop. Potable water can be utilized as a supply source for both sectors but recycled water cannot supply high-quality demands.

The coastal groundwater aquifer is modeled as a renewable and replaceable resource, characterized by a lens of freshwater floating on underlying seawater. The head level (h), or the distance between the top of the lens and mean sea level, serves as a measure of the aquifer stock. As the freshwater stock declines the head level falls and extraction becomes more costly since water must be lifted further to reach the ground surface. Thus, unit extraction cost is a non-negative, decreasing, convex function of head, i.e. $c_G(h) \geq 0$, $c'_G(h) < 0$, and $c''_G(h) \geq 0$.

Leakage from a coastal aquifer is also a function the head level—as the head level declines leakage decreases both because of a smaller surface area along the ocean boundary and because of the decrease in pressure due to shrinking of the lens. Thus, leakage is a positive, increasing, convex function of head, i.e. $l(h) \geq 0$, $l'(h) > 0$, and $l''(h) \geq 0$. We assume that infiltration from precipitation and adjacent water bodies is fixed at a constant rate (I). The resource is “renewable,” therefore, in that *net recharge* (recharge minus leakage) varies with the groundwater stock.

For satellite recycling facilities developed near concentrated groups of users (e.g., industrial parks), the timing of distribution-infrastructure construction coincides with that of the treatment facility. Given sufficient data on infrastructure (e.g., connections, pipes, and treatment plants) and variable costs, amortization methods can be applied to determine a constant unit cost of recycled water (c_R).

The water manager chooses the rates of groundwater extraction for use in the household sector (q_t^{GH}) and the non-household or “other” sector (q_t^{GO}), the rates of seawater desalination for household (q_t^{BH}) and non-household use (q_t^{BO}), and the rate of water recycling (q_t^{RO}) for use in the non-household sector to maximize the present value of net social benefit, measured as the sum of consumer and revenue surplus or equivalently gross consumer surplus less total costs, i.e.

$$\text{Max}_{q_t^{GH}, q_t^{BH}, q_t^{GO}, q_t^{RO}, q_t^{BO}} \int_0^{\infty} e^{-\delta t} \left\{ \int_0^{q_t^{GH} + q_t^{BH}} D_H^{-1}(x, t) dx + \int_0^{q_t^{GO} + q_t^{RO} + q_t^{BO}} D_O^{-1}(x, t) dx - \left((q_t^{GH} + q_t^{GO}) c_G(h_t) - (q_t^{BH} + q_t^{BO}) c_B - q_t^{RO} c_R \right) \right\} dt \quad (1)$$

$$\text{subject to } \gamma \dot{h}_t = I - l(h_t) - (q_t^{GH} + q_t^{GO})$$

where $D_i^{-1}(\bullet)$ is the inverse demand function for sector $i=H,O$, δ is the positive discount rate, c_B is the unit cost of desalinated seawater, c_R is the unit treatment and distribution cost of recycled wastewater, and γ is a height-to-volume conversion factor.

In solving the model (Eq. 1) we find that the objective of welfare maximization can be achieved by using the available resources in reverse order of their marginal opportunity costs (MOC) within each sector. In other words, the pricing rule that induces optimal consumption in both sectors is

$$\begin{aligned} p_t^H &= \min\{c_G(h_t) + \lambda_t, c_B\} \\ p_t^O &= \min\{c_G(h_t) + \lambda_t, c_R, c_B\} \end{aligned} \quad (2)$$

where p_t^i is defined as the marginal benefit of water consumed in sector i , and λ_t is the shadow price or marginal user cost of groundwater. While the MOCs of recycled and desalinated water are constant, the MOC of groundwater is variable, since unit extraction cost rises as the aquifer head level declines and the marginal user cost rises as the resource becomes scarcer. The stages of resource uses leading up to the long-run equilibrium or steady state will be determined by the ordering of the three MOCs (Eq. 2), as well as the shape of the variable groundwater MOC path over time.

Numerical Computations

The model is solved numerically by iterating forward through time. Growing demand in both sectors ensures eventual implementation of desalination and recycling, since the size of the aquifer is finite. The initial head level is given by field measurements, and the terminal head level is obtained from steady-state calculations. Given these boundary conditions the optimal paths will be determined once we know the correct initial shadow price of groundwater. Using a shooting method, we start with an educated guess for the initial shadow price. Governing equations for the head level and price allow one to characterize the entire paths of water use and aquifer stock. If one or more of the resulting terminal values is inconsistent with the optimal steady state conditions, then the initial guess for the shadow price must be adjusted and the process repeated. The trajectory is optimal once all of the boundary conditions are simultaneously satisfied.

Principle Findings and Significance

Analytical Results

There are several possible orderings of resource use, depending on the MOC paths in Eq. 2. If groundwater is sufficiently abundant that the initial marginal opportunity cost of groundwater (MOC^G) lies below both the unit costs of desalination and recycling, then stage 1 is characterized by exclusive groundwater use in both sectors (scenario A). The high rate of combined extraction raises MOC^G , and recycled water is implemented as a sector-specific backstop for the non-household sector in period T_1 . Groundwater continues to supply the household sector in stage 2 but all non-household needs are met by recycled water. At the second switch-point (T_2), MOC^G reaches the unit cost of desalination, and the system reaches a

steady state. Desalinated water supplements groundwater in the household sector and recycled water is used exclusively by the non-household sector in the steady state.

If the aquifer has already been depleted, such that $MOC^G > c_B > c_R$ in the initial period, then both “backstops” are used at the outset to allow the aquifer to replenish in stage 1 (scenario B). Once the head level rises enough to allow MOC^G to decline to c_B , extraction of groundwater commences. Any extraction greater than net recharge, however, would raise MOC^G above the unit cost of desalination and would thus be non-optimal. That is, it would be more cost-effective to use desalinated water in place of those last units of groundwater.

Thus, the system immediately reaches a steady state in which extraction is exactly equal to aquifer inflow, and the optimal quantity of water demanded for the non-household sector is met entirely by recycling.

A third possibility is that $c_B > MOC^G > c_R$. In that scenario (C), groundwater is extracted for the household sector at the outset, but recycled water is used exclusively in every period for the non-household sector. The MOC of groundwater eventually rises to the unit cost of desalination at which point the aquifer reaches a steady state. Extraction is limited to net recharge so that the head level is maintained and the remainder of the quantity demanded by the household sector is supplied by desalination. The stages of each scenario are summarized in Table 1 and hypothetical MOC paths for scenario A are illustrated in Figure 1.

Table 1. Stages of resource use with constant unit recycling cost.

Scenario/Stage	1	2	3
A	GW for H GW for O	GW for H RW for O	GW + DW for H RW for O
B	DW for H RW for O	DW + GW for H RW for O	
C	GW for H RW for O	GW + DW for H RW for O	

Note: GW = groundwater, DW = desalinated water, RW = recycled water, H = household sector, O = non-household sector

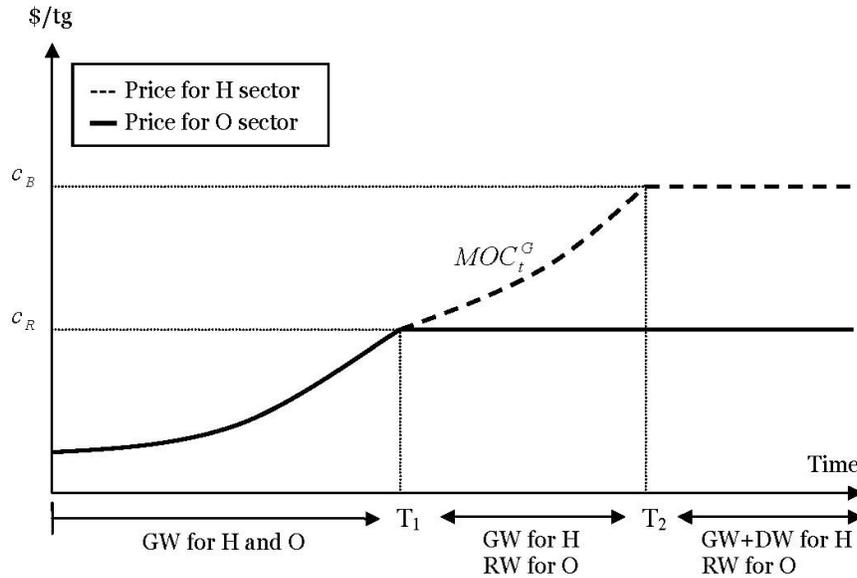


Figure 1. Hypothetical MOC paths for scenario A.

Empirical Results

In an application to the Pearl Harbor aquifer and consumption district on the island of Oahu, Hawaii, we characterize the paths of resource use when recycling is implemented optimally, implemented non-optimally or “prematurely” from the outset, and never implemented (Figure 2). The extraction structure for the optimal solution is consistent with the paths described in hypothetical scenario A. Since Pearl Harbor aquifer is currently above its optimal steady state, the scarcity value of groundwater starts low, and groundwater is initially used in both sectors. In year 75 the scarcity value reaches c_R , and the non-household sector shifts to the use of recycled water. The household sector continues to use groundwater exclusively for the next decade, and the price of groundwater continues to rise. At year 85 the system reaches a steady state—groundwater extraction is limited to net recharge, and the remaining optimal quantity demanded by the household sector is supplied by desalination.

If instead recycled water is utilized by the non-household sector from the outset, the aquifer is allowed to build up much higher than in the optimal case. Extraction is relatively low for the first 80 years because the non-household sector never uses groundwater. Total consumption is also lower for the first 60 years because, although groundwater is less scarce for the household sector, the high recycled water price for the non-household sector induces excessive conservation. When groundwater is optimized without consideration of water recycling, extraction is lower, total consumption is lower, and the scarcity value of groundwater is higher in every period.

The welfare gains from implementing an optimal water recycling program can be substantial. In this particular case study the net present value of social benefits (NPV) derived from the

optimal program is approximately \$1.173 billion. When groundwater is optimized alone the NPV is \$1.166 billion, a difference of \$67 million in present-value terms.

Recycling increases welfare by prolonging the use of groundwater before the steady state and thus delays the implementation of costly desalination for the household sector. Alternatively, if recycling is implemented prematurely, the NPV is \$1.123 billion, nearly \$500 million less than in the optimal case. Although early recycling delays desalination by 6 years, the NPV is still 4.5% lower because costly recycled water is used too soon. Water recycling has the potential to increase total welfare, but economic optimality may entail delaying implementation, depending on how the marginal opportunity cost of recycled water compares to that of groundwater.

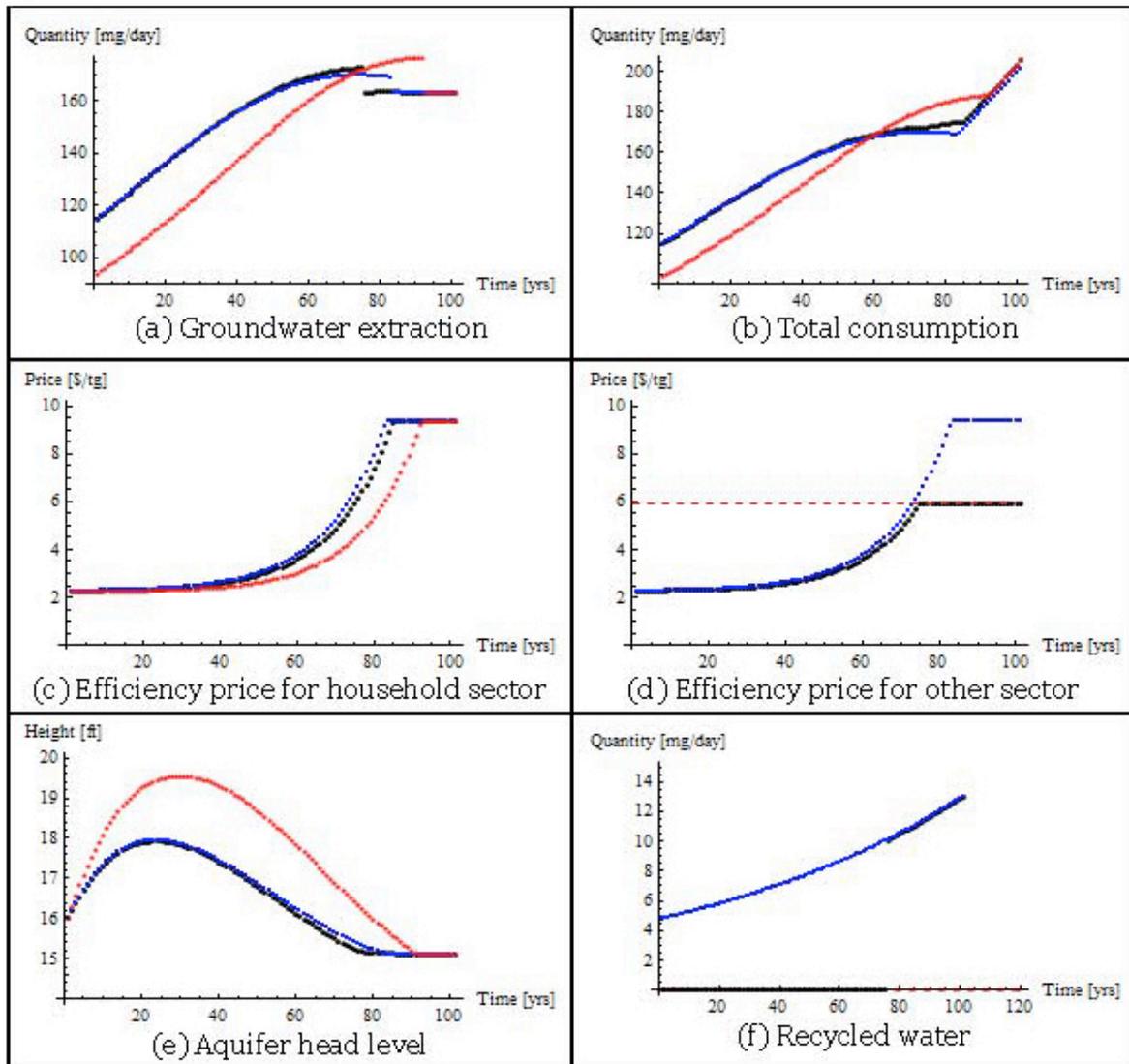


Figure 2. Various time paths for three recycling scenarios: optimal (black), none (blue), premature (red).

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Grant No. G09AC00316 Numerical Simulation of the Effects of Borehole Flow on Measured Vertical Salinity Profiles from Deep Monitor Wells, Pearl Harbor Aquifer, Oahu, Hawaii

Basic Information

Title:	Grant No. G09AC00316 Numerical Simulation of the Effects of Borehole Flow on Measured Vertical Salinity Profiles from Deep Monitor Wells, Pearl Harbor Aquifer, Oahu, Hawaii
Project Number:	2009HI284S
Start Date:	8/1/2009
End Date:	3/31/2011
Funding Source:	Other
Congressional District:	Hawaii 1st
Research Category:	Ground-water Flow and Transport
Focus Category:	Groundwater, Models, Water Quality
Descriptors:	Borehole Flow, Deep Monitor Wells, Salinity Profiles, SEAWAT Model
Principal Investigators:	Aly I El-Kadi

Publications

1. A final report will be published in the U.S. Geological Survey Scientific Investigations Report series.
2. Rotzoll, K., D.S. Oki, and A.I. El-Kadi, 2010, "Numerical simulation of borehole flow in deep monitor wells, Pearl Harbor aquifer, Oahu, Hawaii," Abstract H43A-1219, presented at 2010 Fall Meeting, AGU, San Francisco, CA, 13–17 Dec.
3. Rotzoll, K., Numerical simulation of borehole flow in deep monitor wells in a coastal freshwater lens, Pearl Harbor aquifer, Oahu, Hawaii, U.S. Geological Survey Scientific Investigations Report. (in review)

Introduction

The Pearl Harbor aquifer is the most important aquifer on the island of Oahu and currently supplies about 100 mgd of fresh groundwater mainly for public use. Decisions related to future infrastructure development and alternate sources of freshwater, including desalinization, will depend on the long-term sustainability of the groundwater resources in the Pearl Harbor aquifer.

It is critically important, from both economic and resource standpoints, to have an accurate understanding of how much fresh groundwater in the Pearl Harbor aquifer can be developed for future needs. An existing memorandum of agreement between the Honolulu Board of Water Supply, the State Department of Land and Natural Resources Commission on Water Resource Management, and the U.S. Geological Survey recognizes the need to 1) “ensure protection of the groundwater resources in light of uncertainties surrounding the sustainable yield estimates,” 2) calibrate and refine future “next generation” numerical models, and 3) optimize the use of new and existing wells. This study addresses all three of these critical needs.

The status of the fresh groundwater resource in the Pearl Harbor aquifer is commonly assessed through vertical profiles of salinity from deep monitor wells. These profiles provide information on the thickness of the fresh groundwater body at the time the profile is collected. Furthermore, monitoring over time provides information on changes of the freshwater thickness under variable groundwater withdrawals or recharge. By monitoring changes in the freshwater thickness over time, water managers can determine appropriate withdrawal rates from production wells. Vertical salinity profiles also represent valuable data for calibration of numerical groundwater models designed to simulate density-dependent groundwater flow and transport in coastal aquifers (e.g., Souza and Voss 1987, Oki et al. 1998). These models provide insights into groundwater availability under different recharge and withdrawal scenarios (e.g., Oki 2005, Gingerich 2008).

The underlying assumption in using salinity profiles from deep monitor wells is that the measured vertical distribution of salinity in the borehole is representative of salinity in the adjacent aquifer. However, natural or human-induced vertical hydraulic gradients in the aquifer can produce flow in the borehole. Complex flow patterns exist in boreholes in coastal areas (Paillet and Hess 1995). Flow within a borehole causes water that entered the borehole in one interval to be present in another interval and, thus, the salinity profile obtained from the borehole may not be representative of salinity in the adjacent aquifer.

For cases in which an upward flow exists in a borehole, brackish water or saltwater from deeper zones can cause measured salinity in the borehole to overestimate salinity in the adjacent aquifer in shallower zones. In contrast, for cases in which a downward flow exists, freshwater from shallow zones can cause measured salinity in a borehole to underestimate salinity in the adjacent aquifer in deeper zones. All other factors being equal, higher rates of borehole flow will have a greater effect on the measured salinity profile (Paillet et al. 2002). Salinity profiles from deep monitor wells in Hawaii were evaluated to assess the effects of nearby groundwater withdrawal on borehole flow and salinity (Rotzoll 2010). Step-like

changes in salinity (as indicated by specific conductance) with respect to depth are indicative of borehole flow and are evident in almost all available salinity profiles. Local pumping effects may influence the measured depth of the top of the transition zone, indicated by a specific conductance of 1 mS/cm. Profiles from several deep monitor wells located near pumping wellfields indicate a rise of the apparent top of the transition zone by as much as 600 ft in the monitor well. The upward displacement causes an increase in salinity at a particular depth in the upper part of the profile. The observed increases in salinity correlate with increases in nearby withdrawal rates. The effects of groundwater withdrawals on measured salinity profiles are most pronounced in deep monitor wells located in south-central Oahu, corresponding to the most heavily pumped part of the aquifer where deep monitor wells are commonly located in close proximity to production wells.

In contrast to the step-like changes in salinity profiles produced by nearby groundwater withdrawal, borehole flow induced by regional aquifer flow gradients cannot be evaluated from the shape of measured salinity profiles because subtle flows may displace the entire water column in boreholes and conspicuous steps may not be evident. A regional trend in borehole-flow direction, characterized by a general downward-flowing component in areas of recharge (inland) and a general upward-flowing component in areas of discharge (coastal), is expected from a consideration of basin-wide groundwater flow dynamics. Numerical modeling represents a promising approach to quantify the effects of regional aquifer flow on salinity profiles from deep monitor wells in Hawaii.

Problem and Research Objectives

A recent numerical-modeling study of coastal wells in Israel indicates an upward displacement of the borehole salinity in wells located in the coastal-discharge area of the aquifer while it is at a steady-state condition. Responding to the influence of ocean tides the vertical flow in the borehole changes direction and the flow in the monitor well is three orders of magnitude larger than that in the aquifer. This indicates that the observed borehole salinity does not accurately represent the aquifer salinity (Shalev et al. 2009). Therefore these monitor wells do not accurately monitor the actual freshwater-saltwater transition zone.

The overall objective of this study is to provide information on how representative measured vertical salinity profiles from deep monitor wells are of conditions in the adjacent aquifer. A numerical modeling approach, incorporating the hydraulic characteristics and recharge data representative of the Pearl Harbor aquifer, will be used to evaluate the effects of borehole flow on measured salinity profiles from deep monitor wells. Borehole flow caused by vertical hydraulic gradients associated with both the natural regional flow system and with local groundwater withdrawals will be simulated. Model results will be used to estimate differences between vertical salinity profiles in open boreholes and the adjacent aquifer in areas of downward, horizontal, and upward flows within the regional flow system—in areas both with and without nearby pumped wells. Results from this study will provide insights into the magnitude of the discrepancy between current vertical salinity profiles from deep monitor wells and the actual salinities of adjacent aquifers. Such data is critically needed for management and predictive modeling purposes.

Methodology

A three-dimensional numerical model, SEAWAT Version 4 (Langevin et al. 2007), capable of simulating density-dependent groundwater flow and solute transport will be used in this study. Although the model will mainly be conceptual in nature and incorporate a simplified geometry, previously published values for hydraulic characteristics and recharge representative of the Pearl Harbor aquifer will be tested. A steady-state condition that generally represents the distribution of measured water levels in the aquifer will be simulated and used as an initial condition for all other simulations.

Within the model, deep open boreholes will be introduced at selected sites within the natural regional flow system in areas of downward, horizontal, and upward flows. Flow within the borehole will be simulated with a suitable model for an open conduit. Simulated salinity profiles within the borehole will be compared to 1) the pre-existing distribution of salinity in the aquifer without the borehole and 2) the distribution of salinity in the aquifer with the borehole present. The effects of the borehole on saltwater intrusion into the aquifer will also be quantified.

Additionally within the model, pumped wells will be introduced at selected distances from the open boreholes to evaluate the immediate effects of groundwater withdrawals on salinity profiles and saltwater intrusion into the aquifer. The depths of simulated pumped wells will correspond to the depths of typical production wells in the Pearl Harbor aquifer. The effects of both vertical wells and horizontal shafts will be simulated. Pumped wells will be located about 100 and 5,000 ft from the open boreholes and groundwater-withdrawal rates of about 1 and 10 mgd will be simulated for each pumped well.

A sensitivity analysis, in which values of hydraulic characteristics are varied one at a time, will be conducted to evaluate how the magnitudes of hydraulic conductivity, dispersivity, and storage values may affect borehole flow. In addition, at least two simulations incorporating low- and high-permeability layers within the aquifer will be simulated.

Principal Findings and Significance

Model results indicate that, with all other factors being equal, greater withdrawal rates, closer withdrawal locations, or higher hydraulic conductivity of the well cause greater borehole flow and displacement of salinity in the well. Borehole flow caused by the natural groundwater-flow system is five orders of magnitude greater than vertical flow in a homogeneous aquifer, and borehole-flow directions are consistent with the regional flow system: downward flow in inland recharge areas and upward flow in coastal discharge areas. Borehole flow and displacement of salinity inside the monitor wells associated with nearby groundwater withdrawals increase compared to cases with the regional flow field alone, depending on location of the pumped well, withdrawal rates, and assumed hydraulic conductivity of the well.

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Publications from Prior Projects

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Determination of the Relationship between Biodiversity and the Trophic State of Wahiawa Reservoir, Phase II

Basic Information

Title:	Determination of the Relationship between Biodiversity and the Trophic State of Wahiawa Reservoir, Phase II
Project Number:	2010HI285B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	Hawaii 1st
Research Category:	Water Quality
Focus Category:	Surface Water, Nutrients, Ecology
Descriptors:	Water Eutrophication, Biodiversity
Principal Investigators:	Clark Liu, Tao Yan

Publications

There are no publications.

Problem and Research Objectives

Traditional trophic state assessment methods for inland waters, which were developed based on a few physical/chemical parameters or composite indices of these parameters, do not address the interactions between abiotic factors and biotic factors. Therefore, they often fail to alert forthcoming problems of algal bloom and eutrophication in lakes or reservoirs receiving nutrients from storm runoff and other pollution sources. In this project, laboratory and field experiments are conducted to simulate trophic changes at the Wahiawa Reservoir on Oahu, Hawaii and to investigate the relationship between trophic states and microbial biodiversity. The working hypothesis is that the eutrophication process, i.e., the transition from oligotrophic to eutrophic and to hypertrophic, corresponds to significant changes of microbial biodiversity.

The principal objectives of this proposal are to:

1. Establish the relationship between trophic states and microbial biodiversity in polluted lakes by laboratory experiments.
2. Select three field sites in Wahiawa Reservoir, which are in varying trophic states and to conduct conjunctive bioproductivity and corresponding studies.
3. Study *Escherichia coli* decay kinetics in Wahiawa Reservoir and the relationship between bioproductivity, biodiversity, and *E. coli* die-off kinetics.

Methodology

Design and operation of lab-scale bioreactor experiments. Three flow-through lab-scale bioreactors were constructed to study how lake productivity and biodiversity are influenced by nutrient inputs. Total phosphorus (TP) was used as the limiting nutrient controlling bioproductivity. By adjusting influent TP and hydraulic conditions of these reactors, three trophic state, i.e., oligotrophic, mesotrophic, and eutrophic, were established in bioreactors. Determination of TP concentrations and other operational conditions, including T_R hydraulic residence time, overflow rate (Q/A), and TP loading (TP/surface area) were based on the Vollenweider model. Parameters to be monitored during the field investigation and laboratory experiments include algae cell numbers, Chl *a*, dissolved oxygen (DO), pH, TN, total organic carbon (TOC), TP and reactive phosphorus, total solids (TS), and turbidity.

Molecular biology and biodiversity analysis. This project follows a molecular approach to characterize prokaryotic and micro eukaryotic biodiversities. PCRs were conducted on an iCycler (Bio-rad, Hercules, CA) to amplify the small subunit ribosomal ribonucleic acid (rRNA) genes (i.e., 16S rRNA or 18S rRNA for prokaryotes and eukaryotes, respectively). The amplified rRNA genes were then visualized using DGGE. Computer-aided image analysis was performed to identify gel bands representing distinct microbial populations. Finally, values of Shannon diversity index were calculated to describe the biodiversity of the water samples.

*Determine the die-off kinetics of *E. coli* in different trophic states.* The experimental approach involves spiking cultivated *E. coli* cells into the three laboratory bioreactors that have developed different trophic states, and monitoring the die-off of *E. coli* cells over time. The laboratory reservoir microcosms will use the same microcosms that were developed in Phase 1 of this

WRRIP project. The bioreactors are to be fed with freshly-obtained Wahiawa Reservoir water as inoculum and operated according to the previously established protocols.

After a short initial mixing to dispense the spiked *E. coli* cells, water samples (10 ml) will be collected from all three bioreactors every 30 minutes. The numbers of viable *E. coli* cells are then to be quantified using EPA's standard method.

Principal Findings and Significance

1. Laboratory Investigation

Major findings that were achieved by laboratory experiments using three bioreactors have been included in the Phase 1 WRRIP project.

2. Field Investigation

Three field sampling sites were selected for the second phase of this WRRIP project.

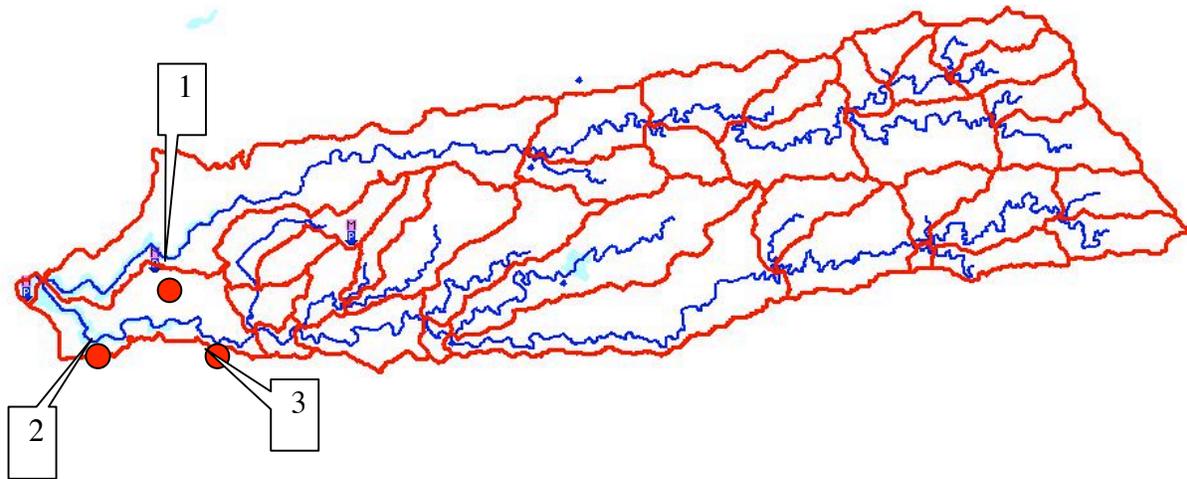


Figure 1. Wahiawa watershed and the selected sampling sites.

Site 1 shows the least biological activity and Site 2 shows the highest biological activity (Table 1). The reservoir is most likely in a mesotrophic state.

Table 1. Water quality of Wahiawa Reservoir.

Site	Chl <i>a</i> (mg/m ³)	TN (mg/L)	TOC (mg/L)	TP (:g/L)	Reactive P (:g/L)	TSS (mg/L)
1	15.3	0.23	3.42	34.9	13.7	5.6
2	23.9	0.35	4.14	58.3	17.7	5.0
3	17.4	0.24	3.35	32.1	11.7	4.3

Water samples collected at these sites were then analyzed to determine their biodiversity. Results of DGGE analysis are shown in Figure 2.

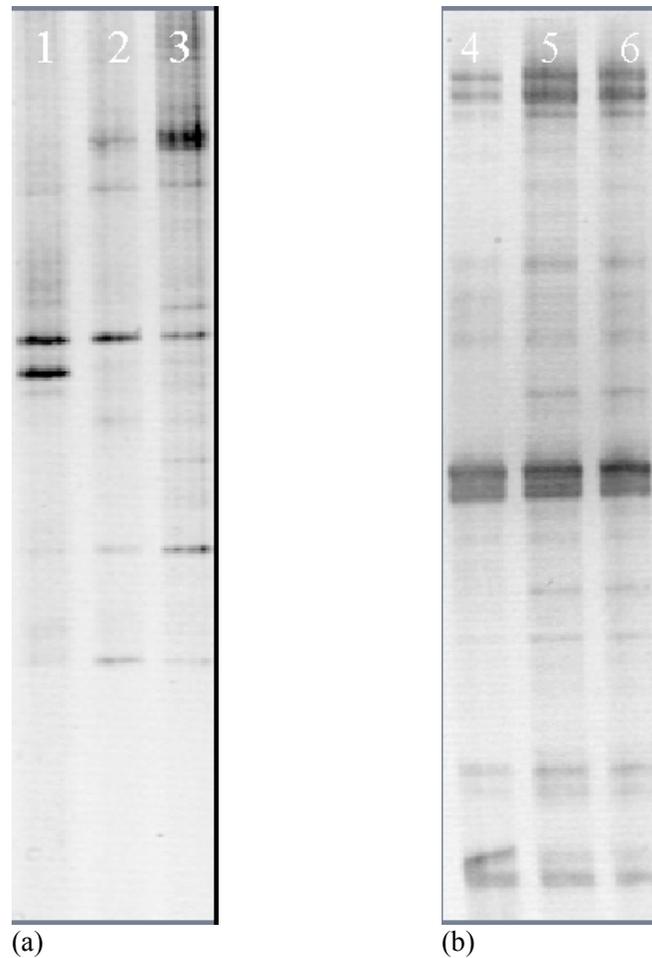


Figure 2. DGGE analysis of 18/16S rDNA fragment for determining the biodiversity in Wahiawa Reservoir by using DGGE band pattern. Image (a): DGGE analysis of 18S rDNA fragment. Image (b): DGGE analysis of 16S rDNA fragment. Lane 1 and Lane 4 are collected in Site 1 of Wahiawa Reservoir; Lane 2 and Lane 5 are collected in Site 2 of Wahiawa Reservoir; Lane 3 and Lane 6 are collected in Site 3 of Wahiawa Reservoir.

Biodiversity of these water samples were further determined by the Shannon diversity index analysis (Table 2). The formula for calculating the Shannon diversity index is:

$$H' = -\sum p_i \ln p_i \quad (1)$$

$$p_i = \frac{n_i}{N} \quad (2)$$

$$E = \frac{H'}{\ln S} \quad (3)$$

where

p_i is the proportional abundance of the i th band

n_i is the intensity(pixel) of band

N : is the total intensity of banding land

E is the evenness

S is the band number (species richness).

Table 2. Biodiversity indices based on DGGE banding data analysis of 18 rDNA/16 rDNA fragment of Wahiawa Reservoir.

Eukaryote				Prokaryote			
Lane	H'	S	E	Lane	H'	S	E
1	1.828	14	0.6926	4	2.452	16	0.8845
2	1.960	12	0.7887	5	2.918	27	0.8855
3	2.621	20	0.8748	6	2.693	21	0.8846

Comparing the results of Tables 1 and 2 indicates that eukaryotes or algae in a polluted reservoir would have a high biodiversity when it is in the state of mesotrophic.

E. coli Kinetics

The *E. coli* die-off experiments were conducted in three bioreactors (Table 3). They indicate that *E. coli* would die-off the fastest in an oligotrophic water and the slowest in an eutrophic water.

Table 3. *E. coli* die-off in three bioreactors of varying trophic levels.

Time (hr)	Oligotrophic		Mesotrophic		Eutrophic	
	Plate 1	Plate 2	Plate 1	Plate 2	Plate 1	Plate 2
0	1451	1728	1640	1431	1735	1704
3	109	149	438	371	650	694
7	1	1	67	68	91	396
11	1	1	57	85	1	2

Note: Data = number of colonies present.

Cleaning up Oahu's Coastal Waters, the Role of Tube-Building Polychaetes in Sediment Dynamics

Basic Information

Title:	Cleaning up Oahu's Coastal Waters, the Role of Tube-Building Polychaetes in Sediment Dynamics
Project Number:	2010HI287B
Start Date:	3/1/2010
End Date:	2/1/2011
Funding Source:	104B
Congressional District:	Hawaii 1st
Research Category:	Biological Sciences
Focus Category:	Acid Deposition, Conservation, Sediments
Descriptors:	Invasive Algae Removal, Tube-Building, Sediments Dynamics
Principal Investigators:	Julie Helen Bailey-Brock

Publications

1. Magalhães, W.F., J.H. Bailey-Brock, and J.S. Davenport, 2011, "On the genus *Raphidrilus* Monticelli, 1910 (Polychaeta: Ctenodrilidae) with description of two new species," *Zootaxa* 2804, 1–14.
2. Magalhães, W.F., and J.H. Bailey-Brock, "Macrofaunal assemblages associated with the invasive alga *Avrainvillea amadelpha* (Udoteaceae, Chlorophyta) on the south shore of O‘ahu, Hawaiian Islands." (in preparation)
3. Magalhães, W.F., and J.H. Bailey-Brock, "A new species of *Protocirrinieris* (Polychaeta: Cirratulidae) from Hawaii and a redescription of *Protocirrinieris nuchalis* (Ehlers, 1907)." (in preparation)

Problem and Research Objectives

The natural dynamics of marine sediments and their associated biota are affected by human disturbance in coastal waters. These areas receive drainage from land, groundwater incursion, periodic stream runoff, and may be influenced by sewage injection wells, cesspools and seasonal high surf. Reefs and adjacent beaches are heavily used for recreation, boat traffic and fishing along the south shore of Oahu, Hawaii and on the other Hawaiian Islands. Changes to these reefs over the last three decades include increased terrigenous inputs due to development in the watershed, the accidental introduction of non-native algae and benthic invertebrates to the reef fauna and the reduced abundances of corals, fish and octopus due to overfishing and habitat loss or changes in the habitat.

Since the early 1980's, *Avrainvillea amadelpha*, an introduced alga, was reported on the southeast shore of Oahu. It is now considered one of the most widespread invasive nonindigenous species in Maunalua Bay, Oahu (Coles et al. 2002). This species inhabits soft bottom habitats co-occurring with the endemic Hawaiian sea grass *Halophila hawaiiiana* (Smith et al. 2002) and is a serious environmental threat to local marine communities.

Efforts to remove introduced algae from reefs in Kaneohe Bay and off Waikiki have been ongoing with some success (Smith et al. 2004). However, the assemblage of invertebrate taxa associated with these algae has not been thoroughly investigated to ascertain if native and/or introduced species are a part of the community. These benthic invertebrate assemblages may be affected by the presence of invasive algae, which may enhance (Argyrou et al. 1999) or decrease (Streftaris and Zenetos 2006) local diversity.

Avrainvillea amadelpha mats typically serve as a substrate for many native epiphytic algae (Smith et al. 2002). This association is known to increase the diversity of associated faunal assemblages by providing food and shelter (Duffy 1990), increasing the physical complexity of the habitat and providing a refuge from fish predation (Dean and Connell 1987), providing greater availability of surface area (McGuinness and Underwood 1986) and by reducing the impact from wave exposure (Dommasnes 1968).

The principal objectives of this proposal are to:

1. Characterize the macrobenthic communities associated with the invasive alga *Avrainvillea amadelpha* in a reef flat on Oahu's south shore.
2. Characterize the macrobenthic communities of the surrounding sediments.
3. Verify if there are differences between the macrobenthic communities associated with the invasive alga and those living in bare sediments using analysis of similarity.
4. Understand the distribution of some endemic and more widely distributed species that characterize these communities prior to invasive algal removal efforts.

Methodology

Study Area

This study was carried out on the south shore of Oahu on the nearshore reef flats in Maunalua Bay (Figure 1). The area is predominantly composed of consolidated limestone reef flats covered by a shallow substratum of fine to coarse sand.

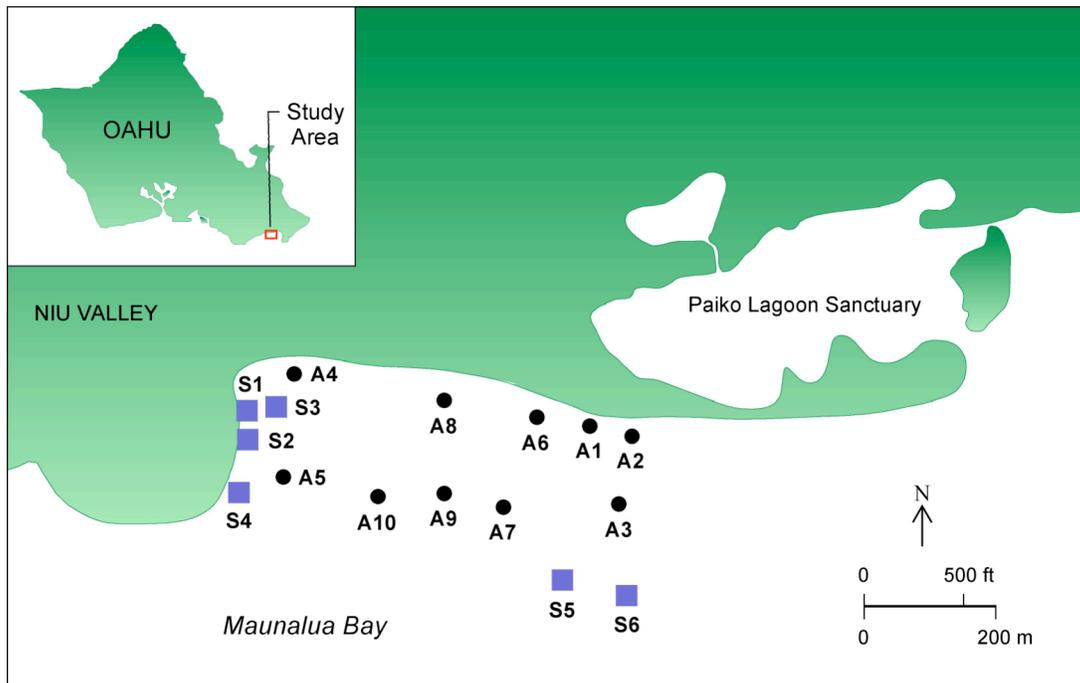


Figure 1. Map of the study area showing the algae (circles) and sediment (squares) stations.

Sampling Design and Macrobenthic Assemblages Survey

Sixteen sampling stations were selected for this study; ten stations (A1–A10) were distributed in areas where *Avrainvillea amadelpha* occurs abundantly and six stations (S1–S6) were placed on sand patches without any algal growth. Three replicates of approximately 475 cm³ each were collected in March 2010 at each station by hand using a Nalgene corer (11 cm in diameter × 5 cm deep). The *Avrainvillea amadelpha* samples (A stations) were composed of sediment to a depth of 5 cm and the overlying algae within the corer. The sediment samples (S stations) were collected with the same Nalgene corer and comprised the top 5 cm of sediment.

All samples were fixed in buffered 10% formalin in water and in a Rose Bengal mixture immediately after sampling for a minimum of 48 hours. Organisms were carefully removed from the crevices and blades of the algae, and placed in 70% ethanol. The algal and sediments were then elutriated with tap water over a 0.5 mm sieve. The organisms retained on the sieve were placed in 70% ethanol. Using compound and dissecting microscopes, the organisms were sorted by major taxa, counted and identified to the lowest taxonomic level possible.

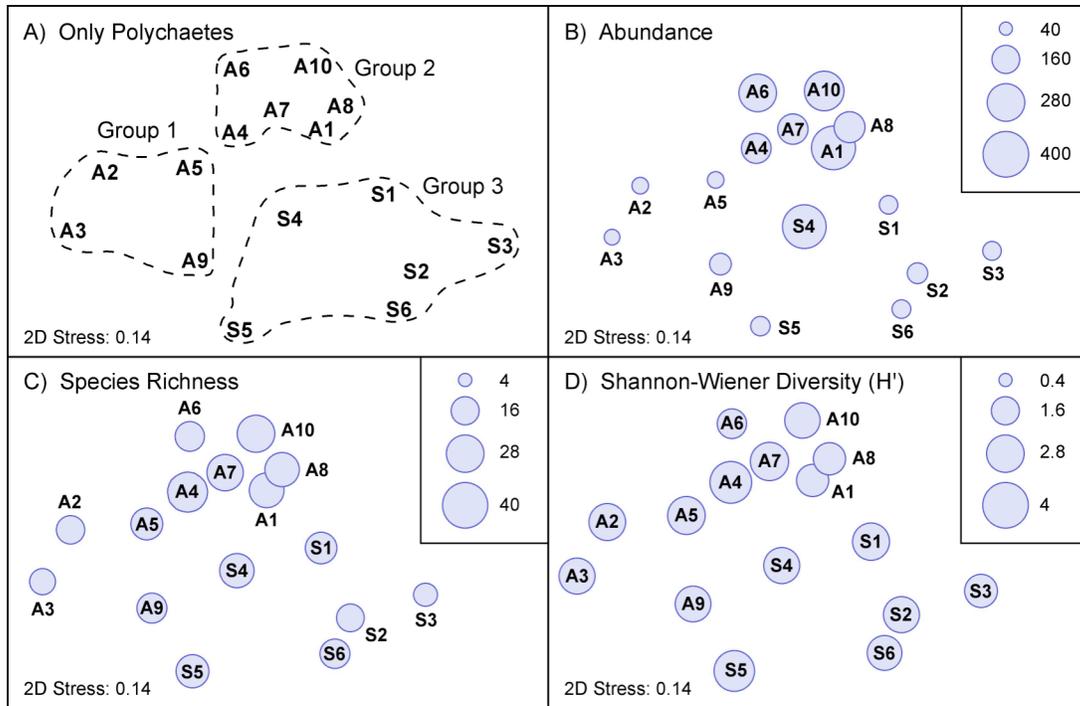
Data Analyses

The replicates within each station were pooled and the abundance (N), species richness (S), and Shannon-Wiener diversity index (H') were calculated for each station. Non-metric Multidimensional Scaling (nMDS) was constructed to produce two-dimensional ordination plots and show relationships among assemblages of all invertebrates and polychaetes, excluding the other taxa. Since the general pattern using both matrices was very similar, we used only the polychaete species structure in the multivariate analysis due to its better taxonomic resolution.

An analysis of similarity (ANOSIM) was performed to verify if the patterns observed in the nMDS ordinations were statistically significant. Similarity percentage analysis (SIMPER) was used to determine the taxa contributing the most to the dissimilarity between groups. All multivariate analyses dealing with biological data were done using the Bray-Curtis similarity coefficient with non-standardized and fourth root transformed data in the PRIMER 6.0 software.

Principal Findings and Significance

1. The macrobenthic assemblages associated with the green invasive alga *Avrainvillea amadelpha* and surrounding sediment patches were very diverse and abundant with a total of 13,607 macrobenthic organisms collected representing 106 taxa.
2. Two new species of polychaete worms were discovered from samples taken from this project, *Raphidrilus hawaiiensis* and *Protocirrinieris* sp. nov.
3. *Avrainvillea amadelpha* mats are a suitable habitat for macrobenthic organisms at this location, especially those detritus feeders favored by the fine sediment coating accumulated on the branches and in crevices of the alga. This green alga housed a large diversity of organisms and seemed to serve as a permanent habitat for several crustaceans, nematodes, and polychaetes.
4. The sampling stations were separated into three groups that were significantly distinct in terms of composition of organisms (Figure 2, Table 1). Group 1 comprised of stations on *Avrainvillea amadelpha* mats with low abundance of polychaetes and characterized by the presence of the syllids *Sphaerosyllis densopapillata* and *Branchiosyllis exilis*, and the eunicid *Nematonereis unicornis*. Group 2 was characterized by stations on *A. amadelpha* mats with higher abundance of polychaetes and the presence of the syllids *S. densopapillata*, *Exogone verugera* and *Exogone longicornis*. Group 3 was characterized by stations on surrounding sediments without *A. amadelpha* and by the presence of the syllids *S. densopapillata* and *E. longicornis* and the endemic lumbrinerid *Lumbrineris dentata*.



Note: Station samples (circle) for plots: B represents the abundance of polychaetes in number of individuals (ranging from 40 to 400), C represents the richness of polychaetes in number of species (ranging from 4 to 40), and D represents the diversity of polychaetes (ranging from 0.4 to 4).

Figure 2. Comparison of nMDS ordinations for polychaete species by: A) Sampling groups, B) Abundance, C) Species richness, and D) Shannon-Wiener diversity (H').

Table 1. Top five polychaete species typical of each group, based on SIMPER.

	Group 1	Group 2	Group 3
	<i>S. densopapillata</i> (Syllidae) (16.82%, 16.98)	<i>S. densopapillata</i> (Syllidae) (13.75%, 3.58)	<i>S. densopapillata</i> (Syllidae) (16.89%, 4.33)
	<i>B. exilis</i> (Syllidae) (12.40%, 6.46)	<i>E. verugera</i> (Syllidae) (7.93%, 7.78)	<i>L. dentata</i> (Lumbrineridae) (10.12%, 3.60)
	<i>N. unicornis</i> (Eunicidae) (12.32%, 6.27)	<i>E. longicornis</i> (Syllidae) (7.57%, 5.80)	<i>E. longicornis</i> (Syllidae) (9.01%, 6.50)
	<i>E. verugera</i> (Syllidae) (12.20%, 4.63)	<i>A. intermedia</i> (Opheliidae) (7.14%, 9.62)	<i>T. cornuta</i> (Syllidae) (8.86%, 1.23)
	<i>Scyphoproctus</i> sp. (Capitellidae) (16.43%, 0.91)	<i>T. cornuta</i> (Syllidae) (6.89%, 8.02)	<i>Paraonella</i> sp. (Paraonidae) (8.65%, 5.05)
Mean No. of Species/Group	48.73 %	55%	47.96%

Note: Percentage of species and ratio (n) of average similarity to standard deviation of similarities indicated in parenthesis.

5. Several polychaete worms, including the tube builder *Mesochaetopterus minutus*, were predominantly collected in the sediment patches without algal growth. *M. minutus* is a gregarious worm that forms tufts of sand-covered tubes and is mainly found on shallow water reef flats along Oahu's south shore (Bailey-Brock 1979, Bailey-Brock 1987). This species might play an important role in these assemblages by binding the sediments loosened by the algal removal efforts in and around their tubes.
6. Current efforts to remove the attached *A. amadelpha* in the study area might destabilize the existing assemblages and recruitment to the cleared area of the reef, but further collections after the removal efforts are necessary to reach any conclusion. This study was conducted right before the first clearing of invasive alga from the area and represents important baseline information to understand the resilience of this ecosystem.

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A Decision Support Tool for Managing the Pipe Network of the Honolulu Board of Water Supply (Year 2)

Basic Information

Title:	A Decision Support Tool for Managing the Pipe Network of the Honolulu Board of Water Supply (Year 2)
Project Number:	2010HI288B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	Hawaii 1st
Research Category:	Water Quality
Focus Category:	Water Supply, Management and Planning, Methods
Descriptors:	Asset Management, Main Breaks, Best Management Practices, Bayesian Analysis, Linear Programming, Availability, Reliability, Probability of Failure
Principal Investigators:	V. Amarjit Singh, Chittaranjan Ray

Publications

1. Adachi, S., and A. Singh, 2009, Asset Management for Water Supply Systems, Interim Report, U.S. Geological Survey, University of Hawaii at Manoa Water Resources Research Center, Project #06HQGR0081, Honolulu, Hawaii, 53 p.
2. Adachi, S., and A. Singh, 2010, Bayesian Analysis for Pipe Failure at HBWS, Interim Report, U.S. Geological Survey, University of Hawaii at Manoa Water Resources Research Center, Project #06HQGR0081, Honolulu, Hawaii, 33 p.
3. Adachi, S., and A. Singh, 2010, Proportional Economic Analysis of Pipe Costs at HBWS, Interim Report, U.S. Geological Survey, University of Hawaii at Manoa Water Resources Research Center, Project #06HQGR0081, Honolulu, Hawaii, 33 p.
4. Adachi, S., and A. Singh, 2011, "Pipe Inefficiency at a Water Utility," in Cheung et al. (eds.), Modern Methods and Advances in Structural Engineering and Construction, Proceedings of the 6th International Structural Engineering and Constructions Conference, Zurich, Switzerland, June 21–26. (in press)
5. Adachi, S., and A. Singh, 2011, "Statistical Analysis of Factors Affecting Availability of Water Pipelines," in Canadian Society for Civil Engineering, 3rd International/9th Construction Specialty Conference, Ottawa, Ontario, Canada, June 14–17. (in press)
6. Singh, A., and S. Adachi, "Bayesian analysis for causes of failure at a water utility," Built Environment Project and Asset Management. (submitted 2011, under revision)
7. Singh, A., and S. Adachi, "Expectation analysis of the probability of failure for water supply pipes," Journal of Pipeline Systems Engineering and Practice. (submitted 2010, under revision)
8. Singh, A., and S. Adachi, "Predicting pipe failure using the NHPP Power Law model," Journal of Pipeline Systems Engineering and Practice. (submitted 2011, under review)
9. Singh, A., and S. Adachi, 2010, Expectation Analysis of Probability of Failure for Water Supply Pipes at HBWS, Interim Report, U.S. Geological Survey, University of Hawaii at Manoa Water Resources Research Center, Project #06HQGR0081, Honolulu, Hawaii, 35 pp.

A Decision Support Tool for Managing the Pipe Network of the Honolulu Board of Water Supply (Year 2)

10. Singh, A., and S. Adachi, 2011, "Facility condition index for asset management at a water utility," *American Professional Constructor*. (in press)
11. Singh, A., and S. Adachi, 2011, "Pipe efficiency analysis at a water utility," *Journal of Pipeline Systems Engineering and Practice*, 2(1), 23–34.
12. Singh, A., S. Adachi, and M. Inouye, 2011, "Quality control analysis of downtime and time to repair for water supply pipes," *Built Environment Project and Asset Management*, 1(1). (in press)
13. Singh, A., M. Inouye, and S. Adachi, 2010, *Analysis of Performance Quality for Downtime and Time to Repair at HBWS*, Interim Report, U.S. Geological Survey, University of Hawaii at Manoa Water Resources Research Center, Project #06HQGR0081, Honolulu, Hawaii, 87 pp.
14. Singh, A., M. Inouye, and S. Adachi, 2010, *Efficiency Analysis of Pipe Types*, Interim Report, U.S. Geological Survey, University of Hawaii at Manoa Water Resources Research Center, Project #06HQGR0081, Honolulu, Hawaii, 50 p.

Problem and Research Objectives

The Honolulu Board of Water Supply (BWS) manages the drinking water supply and distribution system for the island of Oahu, Hawaii, serving approximately one million customers with 54 billion gallons of freshwater every year (Chung et al. 2008). In FY 2008–2009 the BWS had a total field operations budget of \$19 million per year. The BWS maintains over 2,000 miles of pipes, and installs approximately 30 miles of pipe annually at an average cost of about \$1.6 million per mile. Over the last 22 years the BWS Oahu water-distribution system has averaged 366 breaks per year. Given the scale of its operations the BWS needs to develop the best management practices (BMPs) for pipe-utility management. Doing so will aid the BWS in deciding which pipes to replace and when, in a more scientific manner.

The following study objectives have been established:

1. Develop a framework of BMPs for pipe-utility management at the BWS to aid in quality control and in prioritizing specific pipelines for replacement. The goal is to improve policy-making at the BWS so that decisions may be made in a more informed and scientific manner.
2. Develop a warning system using indicators; including the cause(s) of current/past pipe breaks, pipe age, pipe diameter, pipe type, and soil type to determine when and where pipes should be replaced.
3. Develop operating-characteristic curves for various pipes showing the number of breaks, the average cost per break per length in ground, and the average age of various pipes.
4. Calculate the reliability of the water-distribution system identifying various pipe ages, various pipe diameters, and various pipe types.
5. Undertake availability analysis, apply process-capability analysis to availability.
6. Undertake Bayesian analysis for the probability of failure of a given pipe age, pipe diameter, pipe type, and soil type.
7. Develop a pipe-replacement prioritization.
8. Develop a facility condition index.

Methodology

Study data will be analyzed using statistical models and quality-control models to aid in decision making for replacing aging water-distribution pipes. As, in some cases, only limited data is available, proportional analysis will be used on the limited data sample. Availability, economic feasibility, and pipe efficiency of various alternative pipings will be studied and reliability/probability of failure of current piping will be examined using historical data maintained by the BWS regarding past water-main breaks.

Principal Findings and Significance

1. Concrete cylinder pipes, when compared to composite pipe systems, were relatively inefficient in performance.
2. Concrete cylinder pipes, when compared to other pipes, were expensive and uneconomical to maintain.
3. Though ductile iron pipes produce the maximum defectives from a repair perspective, overall they were still more efficient and economic than concrete cylinder pipes.
4. Concrete cylinder pipes should no longer be installed for new or replacement use in the Honolulu BWS water-distribution system.
5. The Honolulu BWS would benefit from professional asset management and quality control.

Publications Cited in Synopsis

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Measuring Soil Water Content and Electrical Conductivity Under High Salinity Conditions Using a Novel TDR Method

Basic Information

Title:	Measuring Soil Water Content and Electrical Conductivity Under High Salinity Conditions Using a Novel TDR Method
Project Number:	2010HI292B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	Hawaii 1st
Research Category:	Climate and Hydrologic Processes
Focus Category:	Agriculture, Irrigation, Methods
Descriptors:	Time Domain Reflectometry, Soil Water Content, Electrical Conductivity, Dielectric
Principal Investigators:	Xiufu Shuai

Publications

There are no publications.

Problem and Research Objectives

Approximately one-third of the developed agricultural land in arid and semi-arid regions reflect some degree of salt accumulation, while more than 25% of the 47 million acres of irrigated agricultural land within the U.S. is affected by salinity (Allison 1964, Tanji 1990). Determining the accurate measurement of soil water content and electric conductivity (EC) in highly saline soils can improve the practical operation of irrigation systems, guide the installation of drainage systems, and provide fundamental information for establishing and validating the algorithm of microwave remote sensing of soil moisture. However, the widely used nondestructive in-situ method, time domain reflectometry (TDR), failed to work under high salinity condition.

Feng et al. (1999) proposed an alternative inverse analysis method to analyze the data from the TDR measurements in the frequency domain. They developed a model, the scatter function of a multi-section transmission line, which can theoretically be applied to any salinity condition. This theoretical model estimates the dielectric permittivity (DP), which is then converted to soil water content by calibration. However, there is no published material that specifically explores using the inverse analysis method under high salinity conditions.

The following are the objectives of this research study:

1. Apply the inverse analysis method proposed by Feng et al. (1999) to measure soil water content and EC under highly saline conditions.
2. Examine the accuracy and upper limit of measurability by the inverse analysis method using commercial probes.

Methodology

To achieve these objectives, the study:

1. Conducted laboratory experiments to determine the accuracy and upper limit of the measurability by the inverse analysis method. The NaCl solutions were made by mixing different amount of NaCl with deionized water. The Makiki soil (fine, mixed, active, isohyperthermic typic haplustepts) was taken from a depth of 0 to 5 cm at a site located on the bank of the Makiki Stream, Oahu, Hawaii. The soil water content varied from 0.15 to 0.47 $\text{m}^3 \text{m}^{-3}$, and the soil bulk EC varied from 0.09 to 0.28 Sm^{-1} . The commercial CS605 probe (Campbell Scientific, Inc.) with three rods of 30-cm length, and TDR100 device (Campbell Scientific, Inc.), were used to measure the waveforms of electromagnetic wave propogating along the probe inserted in the NaCl solution or soils. The estimates of DP and EC were obtained from the detailed algorithms for data analysis (Shuai et al. 2009). The upper limit of the measureability by the inverse analysis method was obtained by comparison of the estimates and the results from the materials under actual test conditions.
2. Analyzed the sensitivity of the mathematical models in the inverse analysis method. In high salinity conditions, the direct current conductivity was significant and the transmission line may be viewed as being connected to a resistor between the central rod and outside rods. Instead of using the measured scatter function (S111m), the variation of (1-

$S_{11_{1m}}/(1+S_{11_{1m}})$ was used to illustrate the sensitivity of the inverse analysis method to EC and DP of materials under test conditions.

Principal Findings and Significance

1. The measurement of EC in soils and sodium chloride solutions was inaccurate when EC was higher than 0.35 Sm^{-1} .
2. The measurement of dielectric permittivity of soils and sodium chloride solutions was inaccurate when EC was higher than 0.08 Sm^{-1} .
3. The findings supported the results from the simulation of the scatter function, which was sensitive to EC but not to DP.
4. More work is needed to improve the measurement accuracy of DP in high salinity conditions.

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USGS Award No. G10AP00126 Hydraulic Properties of the Northern Guam Lens Aquifer System, Territory of Guam, USA

Basic Information

Title:	USGS Award No. G10AP00126 Hydraulic Properties of the Northern Guam Lens Aquifer System, Territory of Guam, USA
Project Number:	2010HI316S
Start Date:	6/30/2010
End Date:	12/31/2011
Funding Source:	104B
Congressional District:	Hawaii 1st
Research Category:	Ground-water Flow and Transport
Focus Category:	Groundwater, Hydrology, Water Supply
Descriptors:	Aquifer Parameter Estimation, Tidal Responses, Aquifer Test
Principal Investigators:	Aly I El-Kadi

Publications

There are no publications.

Problem and Research Objectives

The Northern Guam Lens aquifer system is the most important aquifer on the Island of Guam and currently supplies about 40 mgd of fresh groundwater mainly for public-supply. The resident population on the island of Guam has been increasing, and is expected to increase dramatically as the result of a proposed military buildup with as many as 70,000 residents added to the current estimate of about 171,000 residents. The groundwater demand is expected to increase proportionally with the additional population. This has led to concern over the long-term availability of water from the northern Guam aquifer (Gingerich and Jenson 2010).

Hydraulic parameters such as hydraulic conductivity and storage parameters are essential elements of models used to manage groundwater availability and quality. Uncertainty in these parameters can result in erroneous model estimates and potential mismanagement of drinking-water resources. The objective of this work is to estimate aquifer properties of the northern Guam aquifer.

A three-dimensional ground-water flow and transport model will be developed in a subsequent study to evaluate the availability of Guam's groundwater resources under several recharge and withdrawal scenarios. This study will identify hydrologic parameters to constrain numbers that can be used as input for this model.

Methodology

To meet the objective of this study, data from constant-rate aquifer tests and step-drawdown tests will be analyzed to estimate aquifer properties. Known techniques for constant-rate aquifer tests and step-drawdown tests will be applied (Rotzoll et al. 2007). The specific capacity is the ratio of pumping rate to drawdown of a well. If specific capacity is readily available for wells in the Northern Guam Lens Aquifer, an empirical relationship between hydraulic conductivity from aquifer tests and specific capacity can be developed (Rotzoll and El-Kadi 2008). Moreover, tidally-influenced water levels and salinity time-series at discrete depths also are available to estimate aquifer properties (Rotzoll et al. 2008, Presley 2010).

Principal Findings and Significance

Study is ongoing.

Publications Cited in Synopsis

Gingerich, S.B., and J.W. Jenson, 2010, Groundwater availability study for Guam; Goals, approach, products, and schedule of activities, U.S. Geological Survey Fact Sheet 2010-3084, 4 p.

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Rotzoll, K., and A.I. El-Kadi, 2008, “Estimating hydraulic conductivity from specific capacity for Hawaii aquifers, USA,” *Hydrogeology Journal*, 16(5), 969–979.

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Rotzoll, K., A.I. El-Kadi, and S.B. Gingerich, 2008, “Analysis of an unconfined aquifer subject to asynchronous dual-tide propagation,” *Ground Water*, 46(2), 239–250.

Information Transfer Program Introduction

Hawaii and other Pacific Islands face a unique set of environmental and cultural issues in the management of water resources. Fresh water resources are under threat on many islands both from overuse and contamination. Ocean waters in these tropical regions are ecologically sensitive and valuable, and similarly threatened by overuse and pollution.

As population and income grows, and consumer preferences turn toward greater water use, pressure on island water resources grows even more. Thus it becomes ever more critical that those tasked with their protection and management have accurate, up to date information about the condition of these resources. They need this information to make sound decisions regarding the many competing demands on our water and related resources without undue negative impacts on government, business or personal budgets. The mission of the Water Resources Research Center is to study all aspects of water in the islands and to communicate our findings to agencies responsible for water management. The direct audience includes the State Health Department, the State Department of Land and Natural Resources, the county water supply boards, as well as national regulatory and planning agencies. Furthermore as decision makers are strongly influenced by popular opinion, it is important to try to educate the general public about water issues. A good deal of misinformation circulates about water resources, much of it generated by persons or groups advancing self-interested agendas.

Much money, time, and effort has been expended in addressing perceived problems that, when critically examined, have proven not to be problems at all. In order for research to fulfill its potential to assist in water management it is important for the results to reach people who can use it. That is why there is a need for a technology transfer effort at our Center.

Technology Transfer, FY2010

Basic Information

Title:	Technology Transfer, FY2010
Project Number:	2010HI303B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	1
Research Category:	Not Applicable
Focus Category:	None, None, None
Descriptors:	None
Principal Investigators:	Philip Moravcik

Publications

1. Moravcik, Philip. 2010 (May). Bulletin, University of Hawaii at Manoa Water Resources Research Center, 8 pp.
2. Moravcik, Philip. 2011 (January). Bulletin, University of Hawaii at Manoa Water Resources Research Center, 8 pp.

Technology Transfer

Introduction

Hawaii, as one of the nation's less populous states, generates many opportunities for water researchers to directly interact with senior administrators and policy makers. To further the goal of broadening knowledge and appreciation of Hawaii's water resources, WRRC's Technology Transfer Program produces newsletters, organizes biweekly seminars, workshops, and conferences, produces posters and other materials for presentations, and maintains the Center's website. The Program P.I. is active in meeting with agency personnel, assisting with proposal writing, research project implementation, and contributing to report authorship for the Center's research projects.

Technology Problem and Research Objectives

The mandate of the Water Resources Research Center (WRRC) includes an obligation to broadly disseminate the results of its research activities to audiences of local water and wastewater agencies, environmental engineering consultants, other academic researchers, and interested members of the public.

Methodology

The Technology Transfer Office employs a range of media to disseminate the results of research done at the Center. WRRC bulletins; other publications; web site; workshops, meetings, and conferences; and regular biweekly seminars all served to aid the center in transferring to its multiple audiences timely and critical information concerning water-resource research and issues.

Technology Transfer Program

WRRC's Technology Transfer Program activities for the report period included: organization of multiple seminars; production of project bulletins and newsletters; participation in meetings and conferences; and providing water-resources-research information to consultants, students of all levels, and the general public. The program PI also participated in school science fairs, WRRC research projects, research report writing, and refinement of the center's web site.

During this reporting period the Technology Transfer Program produced two newsletters describing research projects and center activities and news. Extensive use was made of the center's large-format printer/plotter, producing posters for display at local, national, and international meetings and conferences. Several of these posters, illustrating the work of graduate student researchers, won awards at meetings.

As it has done for more than twenty years the Technology Transfer Program continues to organize biweekly seminars designed to foster communication among WRRC researchers, students, and the organizational target audience of government agencies, private-sector researchers, and members of the general public with an interest in water-resource issues. Each semester one WRRC faculty member is appointed to organize the seminars with the assistance of the Technology Transfer office, and recruit speakers from university faculty, visiting scientists, government agencies, and private sector firms. Topics thus vary depending on the interests of the coordinator and availability of speakers. Typically the seminars include reports on WRRC projects and discussions by government officials on emerging water-related issues.

The seminars are generally well attended and provide one of the few public forums in the state for the discussion of water issues. The following is a list of the fifteen seminars presented during the reporting period.

Spring Semester 2010

Mar. 5	Jim Roumassett/Chris Wada	University of Hawaii Dept. of Economics	Beyond Sustainable Yield: Managing Multiple Aquifers, Recycling, and Watershed Conservation in the South Oahu Aquifer System
Mar. 19	Scott Higa	Honolulu Seawater Air Conditioning, LLC	Honolulu Seawater Air Conditioning Project
Apr. 9	Weilin Qu	University of Hawaii Mechanical Engineering	Humidification-Dehumidification Seawater Desalination Process Driven by Solar Energy
May 7	Joe Van Ryzin	Makai Ocean Engineering	Ocean Thermal Energy Conversion - Technology Development for Hawaii

Fall Semester 2010

Sept. 2	Derek J. Chow	Chief, Civil & Public Works Branch, US Army Corps of Engineers, Honolulu District	Non-Structural Flood Risk Management Measures
Oct. 7	Carlos Andrade	Director of the Kamakakūokalani Center for Hawaiian Studies, Hawai'i inuiakea	The Ahupua'a and the Myth of Self Sustainability
Oct. 19	Megan Young	Isotope Tracers Project, U.S. Geological Survey, Menlo Park, CA	Environmental Isotope Tracers: Using a Multi-Isotope Approach to Understand Complex Hydrological Problems
Oct. 21	Roger Fujioka	Emeritus Professor, UH	New Paradigms are

		WRRC	Required to Establish and to Implement Water Quality Standards
Nov. 4	Thomas Ka'eo Duarte	Regional Asset Manager of Hawaii Island Ag. lands and Water Resources Manager at Kamehameha Schools, Land Assets Division.	Changing Times & Changing Paradigms: Water in Hawaii
Nov. 15	Herbert H. P. Fang	Chair Professor of Environmental Engineering, University of Hong Kong	Renewable Bio-energy Production from Wastes and Wastewater in China
Nov. 18	Eric M. Enos	Executive Director, Ka'ala Farm, Inc.	Rebuilding the Ahupaua'a in Wai'anae-Bringing Back the Water, the Land, the People, and Haloa

Spring Semester 2011 Seminar Coordinator: Dr. Clark Liu

Jan. 22	Clark Liu	University of Hawaii CEE and Water Resources	Water and energy sustainability in a changing environment: An Introduction
Feb. 5	Roger Babcock	University of Hawaii Civil & Environmental Engineering/WRRC	Island water sustainability: Wastewater treatment, disposal, recycling
Feb. 19	Paul Bishop	Environmental Engineering Program Director, National Science Foundation	The Water-Energy Nexus and NSF Research
Feb. 25	Dr. Tushar Kanti Sen	Lecturer, Chemical Engineering, Curtin University, Perth, Western Australia	Subsurface Colloidal Fines and their Role in Groundwater Contamination"

WRRC Website

The Center's website (www.wrcc.hawaii.edu) is continually updated with new information about WRRC researchers' activities, seminars, reports, meetings, grant announcements, scholarship opportunities, etc.. The site provides information about center facilities and personnel as well as

a database of WRRC publications. A search function provides easy access to the available information. There is a link on the Center's home page that leads to an archive of full-text PDF files of reports written by WRRC researchers since the early days of the Center. This permits extremely easy access to our reports for our clientele. Following a decision by our past director WRRC no longer publishes reports in-house and our researchers submit their reports as articles directly to journals which generally restrict access to these articles. WRRC continues to post the abstracts and publication information about these articles on our website.

Poster Production

The Technology Transfer Program PI assisted numerous center faculty and graduate research assistants in the design and production of posters illustrating research projects for display at meetings and conferences. Several graduate-research-assistant posters were recognized by conference awards during the reporting period.

Media Contact

During the reporting period the Technology Transfer project P.I. responded on several occasions to inquiries from reporters about water and environmental issues. In addition the Technology Transfer Office submitted news releases regarding the research activities of Center faculty to local and national media through the University of Hawaii's media office.

Legislative Testimony

During the reporting period the Technology Transfer project P.I. submitted testimony at the State legislature on several issues pertaining to water and wastewater issues.

USGS Summer Intern Program

None.

Student Support					
Category	Section 104 Base Grant	Section 104 NCGP Award	NIWR-USGS Internship	Supplemental Awards	Total
Undergraduate	3	0	0	0	3
Masters	3	0	0	0	3
Ph.D.	3	0	0	0	3
Post-Doc.	1	0	0	3	4
Total	10	0	0	3	13

Notable Awards and Achievements

Chittaranjan Ray, Interim Director of the Center was elected as the Fellow of American Society of Civil Engineers and became a Diplomate in Water Resources Engineering.

Joseph Kennedy, a University of Hawaii at Manoa undergraduate, was awarded the 2010 L. Stephen Lau Water Research Endowed Scholarship. He is working on a research project examining submarine groundwater discharges along Oahu's south coast.

Publications from Prior Years