Water Resources Research Center
Annual Technical Report
FY 2009

Introduction

Introduction

Water Resources Research Center
University of Hawai'i at Manoa
Annual Technical Report
FY 2009

Among the problems driven by global climate change, none is more important for long-term sustainability than its impact on water resources. Water is essential for sustaining life and commerce. 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.

Water- and energy-related issues both shared with other United States locales and those specific to the island state of Hawai'i are addressed by University of Hawai'i at Manoa (UHM) Water Resources Research Center (WRRC) scientists.

UHM WRRC serves as the focal point for organizing UHM faculty expertise to study the adequacy, integrity, and purity of Hawai'i's offshore recreational waters and onshore potable-water resources. WRRC researchers address issues regarding efficient water usage, enhancing groundwater availability, efficient wastewater management and future 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 -improvement plans, advance knowledge of energy-efficient desalination and other water-treatment processes, connect hydrologic and economic models of aquifer exploitation, and search for new and better indicators of water quality, among other efforts.

While not often recognized, the Hawaiian island of Oahu, politically the City and County of Honolulu, is truly the "canary in the coal mine" for water- and energy-related issues that, in many cases, will be faced by almost all population centers within the U.S. and worldwide sometime in the future...

While the isolation of the Hawaiian Islands makes such things as water shortages and energy failures especially visible, limited water shortages are already a reality for possibly a third of the U.S. population in the western/southwestern states and water-pollution issues are an increasingly recognized problem both there and in the eastern/northeastern states as well. Energy failures have been seen throughout the U.S. over the last decade.

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

Research Program Introduction

The Hawaii NIWR program for FY 2009 funded four new research projects and small allocations for technology transfer and administration. The four new research projects include:

- The development of a "Decision-Support Tool for Managing the Pipe Network..." of a city water-supply system that may find applicability in any of the aging water-supply infrastructures of American population centers;

- The development of a plan for "Optimal Groundwater Extraction and Water Recycling" that is focused on the specifics of the Oahu environment but develops water supply/distribution concepts that will, more and more, need to be addressed worldwide;

- The development of a study "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" that will be specific to Hawaii but useful for other population centers on isolated semi-tropical volcanic islands; and

- The development of a study generating a "Numerical Simulation of the Effects of Borehole Flow on Measured Vertical Salinity Profiles from Deep Monitor Wells, Pearl Harbor Aquifer, Oahu, Hawaii" that will be extremely significant in either supporting or contradicting critical freshwater supply/demand projections that have dictated water-usage policies on Oahu for years--if not decades...

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

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

- The development of an investigation into "Improving Water Resource Assessment in Hawaii by Using LiDAR Measurements of Canopy Structure to Estimate Rainfall Interception";

- The development of a study on the "Integrated Management of Multiple Aquifers in the Face of Climate Change";

- The development of a potentially solar-powered "Humidification-Dehumidification Seawater Desalination" process that may find a future demand from the vast percentage of worldwide populations that live in proximity to seawater coastlines; and

- The development of "...Radar Imagery as Input to a Rainfall-Runoff Model for the Kawela Watershed, Molokai."

WRRC researchers also pursued many other avenues of research funded by city and county, state, and federal agencies and private firms. Non-WRRIP externally-funded projects accounted for over $14 for each $1 from the WRRIP program and university funds added another nearly $11 for each WRRIP dollar.

UHM funds continue to supplement the NIWR funds supporting the noted research projects.

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:	2/28/2010
Funding Source:	104B
Congressional District:	Hawai`i 1st
Research Category:	Engineering
Focus Category:	Water Supply, Treatment, None
Descriptors:	Freshwater supply, seawater desalination, humidification-dehumidification
Principal Investigators:	Weilin Qu

Publications

There are no publications.

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 Hawaiʻi because of the high energy cost. The primary energy source used in Hawaiʻi 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 Hawaiʻi. While its geographical location makes

electricity and high-grade petrochemical-based thermal energy expensive in Hawai‘i, 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. (2005), Shaobo et al. (2005), Xiong et al. (2005), 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. 2006, Li et al. 2006) 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 (WRRIP2008) 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 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.

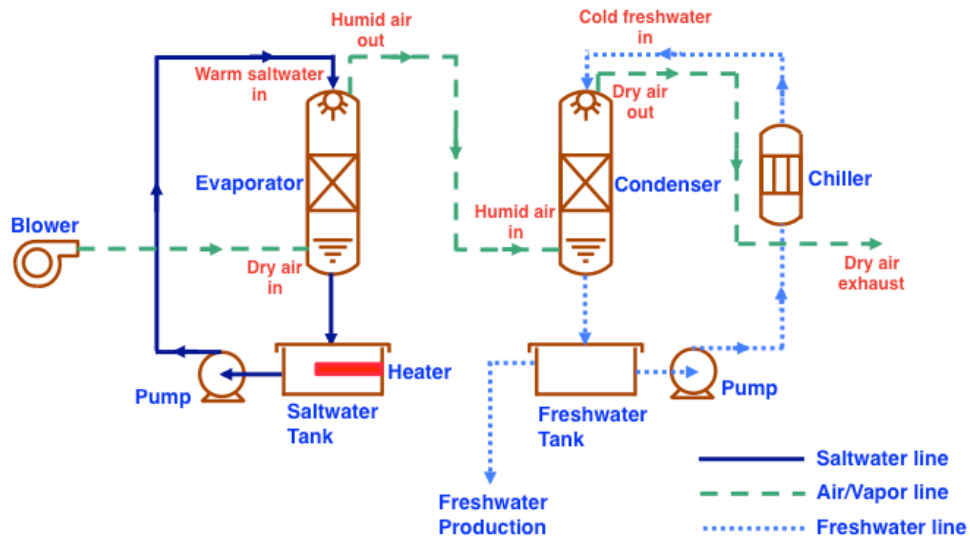

Figure 1. Schematic diagram of HDH desalination lab-scale experimental system.

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.

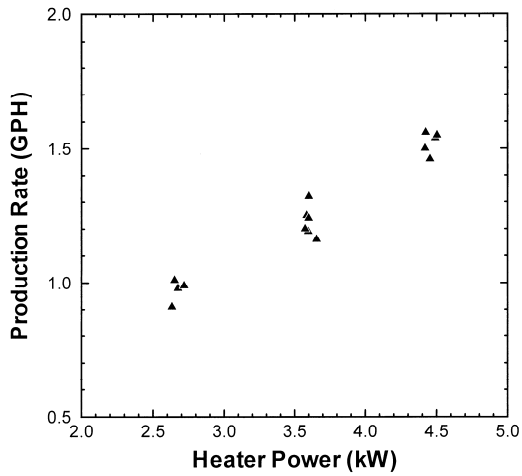

Figure 3. Experimental freshwater-production rate vs. heater-power input to the saltwater.

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.

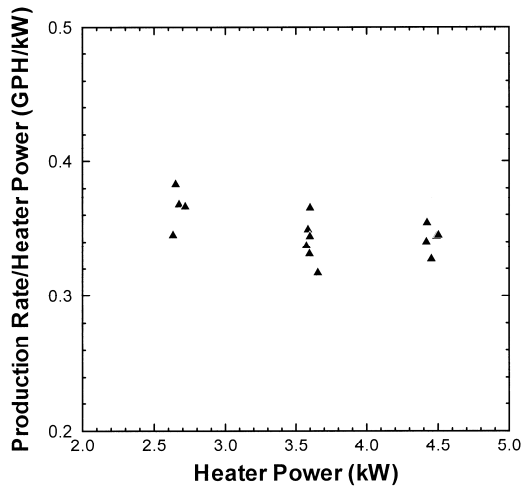

Figure 4. Ratio of freshwater-production rate to heating-power input vs. heater-power input.

The O‘ahu 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 O‘ahu 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.

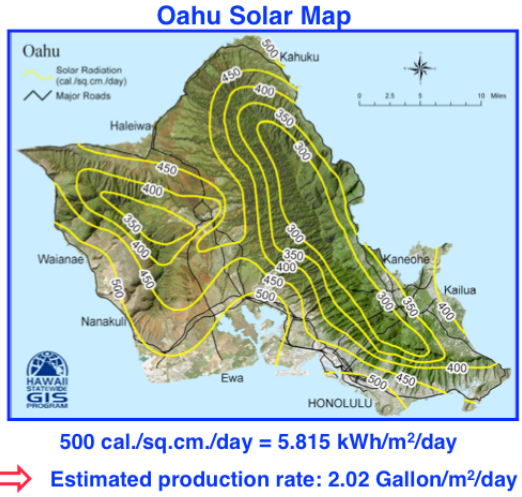

Figure 5. Estimated freshwater-production rate is the experimental system is operating at the O‘ahu Island ‘Ewa plain.

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.

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 desalination systems.

Publications Cited in the Synopsis

Abdel-Salam, M.S., M.M. Hilal, A.F. El-Dib, and M.A. Abdel-Monem, 1993, “Experimental study of humidification-dehumidification desalination system,” *Energy Sources* 15 (3): 475–490.

Al-Hallaj, S., and J.R. Selman, 2002, *A Comprehensive Study of Solar Desalination with a Humidification-Dehumidification Cycle,* Middle East Desalination Research Center Report 98-BS-032b.

Al-Hallaj, S., M.M. Farid, and A.R. Tamimi, 1998, “Solar desalination with a humidification-dehumidification cycle: Performance of the unit,” *Desalination* 120 (3): 273–280.

Assouad, Y., and Z. Lavan, 1988, "Solar desalination with latent heat recovery," *J. Solar Energy Eng*. 110 (1): 14–16.

Bourouni, K., M.T. Chaibi, and L. Tadrist, 2001, "Water desalination by humidification and dehumidification of air: State of the art," *Desalination* 137 (1–3): 167–176.

El-Dessouky, H.T.A., 1989, "Humidification-dehumidification desalination using waste heat from a gas turbine," *Desalination* 71 (1): 19–33.

Goosen, M.F.A., S.S. Sablani, C. Paton, J. Perret, A. Al-Nuaimi, I. Haffar, H. Al-Hinai, and W.H. Shayya, 2003, "Solar energy desalination for arid coastal regions: Development of a humidification-dehumidification seawater greenhouse," *Solar Energy* 75:413–419.

Klausner, J.F., Y. Li, and R. Mei, 2006, "Evaporative heat and mass transfer for the diffusion driven desalination process," *Heat Mass Transfer* 42 (6): 528–536.

Klausner, J.F., Y. Li, M. Darwish, and R. Mei, 2004, "Innovative diffusion driven desalination process," *ASME J. Energy Resour. Technol.* 126 (3): 219–225.

Li, Y., J.F. Klausner, and R. Mei, 2006, "Performance characteristics of the diffusion driven desalination process," *Desalination* 196:188–209.

Li, Y., J.F. Klausner, R. Mei, and J. Knight, 2006, "Direct contact condensation in packed beds," *Int. J. Heat Mass Transfer* 49:4751-4761.

Muller-Holst, H., M. Engelhardt, and W. Scholkopf, 1999, "Small-scale thermal seawater desalination simulation and optimization of system design," *Desalination* 122–123:255–262.

Shaobo, H., Y. Shengquan, and H. Zhang, 2005, "Performance optimization of solar humidification-dehumidification desalination process using pinch technology," *Desalination* 183 (1–3): 143–149.

Xiong, R.H., S.C. Wang, L.X. Xie, Z. Wang, and P.L. Li, 2005, "Experimental investigation of a baffled shell and tube desalination column using the humidification-dehumidification process," *Desalination* 180 (1–3): 253–261.

Xiong, R.H.; S.C. Wang, Z. Wang, L.X. Xie, P.L. Li, and A.M. Zhu, 2005, "Experimental investigation of a vertical tubular desalination unit using humidification-dehumidification process," *Chin. J. Chem. Eng.* 13 (3): 324–328.

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 runs from 1 April 2009 to 31 December 2009. Our research team will collaborate with a local 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:	Hawai`i 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 Hawai‘i 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 on Kaua‘i, 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 Hawai‘i watersheds are the temporal and spatial distribution of rainfall and runoff/infiltration characteristics. Existing watershed modeling studies in Hawai‘i include those on the Mānoa-Pālolo Stream on O‘ahu by Sahoo et al. (2006) and by El-Kadi and Yamashita (2007), on the Mākaha Valley on O‘ahu (Mair et al. 2007), and on the Hanalei watershed on Kaua‘i (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 Hawai‘i 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 Hawai‘i 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 Hawai‘i for use in hydrologic modeling has yet to be tested.

The Kawela watershed, a medium-size watershed on Moloka‘i covering an area of 13.7 km^2, 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 Koʻolau watersheds on Oʻahu 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 (USGS). 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 Molokaʻi, 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, Molokaʻi. 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 Molokaʻi, 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 the USGS Scientific Investigations Report series or 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 Molokaʻi, 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, Moloka‘i.

Preliminary Findings

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

References Cited in the Synopsis

El-Kadi, A.I., and E. Yamashita, 2007, “Modeling streamflows and flood delineation of the 2004 flood disaster, Manoa, Oahu, Hawaii,” *Pacific Science,* 61 (2): 235–255.

Field, M.E., C.J. Berg, and S.A. Cochran, 2007, “Science and management in the Hanalei Watershed: A trans-disciplinary approach,” *Proceedings from the Hanalei Watershed Workshop,* U.S. Geological Survey, Open-File Report 2007-1219, 87 p.

Giambelluca, T.W., M.A. Nullet, and T.A. Schroeder, 1986, *Hawaii Rainfall Atlas,* State of Hawaii, Department of Land and Natural Resources, Division of Water and Land Development, Report R 76, 267 p.

Gorokhovich, Y., and G. Villarini, 2005, “Application of GIS for processing and establishing the correlation between weather radar reflectivity and precipitation data,” *Meteorological Applications,* 12 (1): 91–99.

Kalinga, O.A., and T.Y. Gan, 2006, “Semi-distributed modeling of basin hydrology with radar and gauged precipitation,” *Hydrological Processes,* 20 (17): 3725–3746.

Mair, A., A. Fares, and A.I. El-Kadi, 2007, “Effects of rainfall and ground-water pumping on streamflow in Makaha, Oahu, Hawaii,” *Journal of the American Water Resources Association,* 43 (1): 148–159.

Oki, D.S., 2004, *Trends in Streamflow Characteristics at Long-Term Gaging Stations, Hawaii,* U.S. Geological Survey, Scientific Investigations Report 2004-5080, 120 p.

Peters, J.C., and D.J. Easton, 1997, *Runoff Simulation Using Radar Rainfall Data,* Water Resources Bulletin 32 (4): 753–760.

Polyakov, V., A. Fares, D. Kubo, J. Jacobi, and C. Smith, 2007, "Evaluation of a non-point source pollution model, AnnAGNPS, in a tropical watershed," *Environmental Modeling and Software,* 22 (11): 1617–1627.

Sahoo, G.B., C. Ray, and E.H. De Carlo, 2006, "Calibration and validation of a physically distributed hydrological model, MIKE SHE, to predict streamflow at high frequency in a flashy mountainous Hawaii stream," *Journal of Hydrology,* 327 (1–2): 94–109.

Smith, J.A., M.L. Baeck, K.L. Meierdiercks, A.J. Miller, and W.F. Krajewski, 2007, "Radar rainfall estimation for flash flood forecasting in small urban watersheds," *Advances in Water Resources,* 30 (10): 2087–2097.

Smith, J.A., and W.F. Krajewski, 2002, "Radar hydrology: Rainfall estimation," *Advances in Water Resources,* 25 (8–12): 1387–1394.

Wang, X., H. Xie, H. Sharif, and J. Zeitler, 2008, "Validating NEXRAD MPE and Stage III precipitation products for uniform rainfall on the Upper Guadalupe River Basin of the Texas Hill Country," *Journal of Hydrology,* 348 (1–2): 73–86.

Xie, H., X. Zhou, J.M.H. Hendrickx, E.R. Vivoni, H. Guan, Y. Tian, and E.E. Small, 2006, "Evaluation of NEXRAD Stage III precipitation data over semiarid region," *Journal of the American Water Resources Association,* 42 (1): 237–256.

Xie, H., X. Zhou, E.R. Vivoni, J.M.H. Hendrickx, and E.E. Small, 2005, "GIS-based NEXRAD Stage III precipitation: Automated approaches for data processing and visualization," *Computers and Geosciences,* 31:65–76.

Yates, D.N., T.T. Warner, and G.H. Leavesley, 2000, "Prediction of a flash flood in complex terrain: Part 2: A comparison of flood discharge simulations using rainfall input from radar, a dynamic model, and an automated algorithmic system," *Journal of Applied Meteorology,* 39 (6): 815–825.

A decision support tool for managing the pipe network of the Honolulu Board of Water Supply

Basic Information

Title:	A decision support tool for managing the pipe network of the Honolulu Board of Water Supply
Project Number:	2009HI242B
Start Date:	3/1/2009
End Date:	2/28/2010
Funding Source:	104B
Congressional District:	Hawai`i 1st
Research Category:	Engineering
Focus Category:	Water Supply, Management and Planning, Economics
Descriptors:	
Principal Investigators:	V. Amarjit Singh, Chittaranjan Ray

Publications

1. Adachi, S., and A. Singh, Exemption Required to Show that Procurement by Competitive Means is Neither Practicable nor Advantageous, Interim Report, May 2010 [Being prepared for journal submission].
2. Adachi, Stacy, and Amarjit Singh, 2009, Asset Management for Water Supply Systems, Interim Report, University of Hawai i at Manoa Water Resources Research Center, Summer, pp. 49.
3. Inouye, M., A. Singh, and S. Adachi, Analysis of Downtime and Repair for Water Supply Pipes, Interim Report, May 2010 [Being prepared for journal submission].
4. Singh, Amarjit, and Stacy Adachi, 2010 [under review/revision submitted], Pipe Efficiency Analysis, J. of Pipeline Syst. Engrg. and Pract.
5. Singh A., and S. Adachi, Proportional Economic Analysis of Pipe Costs at a Water Utility, Interim Report, May 2010 [Being prepared for journal submission].
6. Singh, A., Kira-lyn Kow, and S. Adachi, Probability of Pipe Failure at a Public Water Supply Utility, Interim Report, May 2010 [Being prepared for journal submission].

Problem and Research Objectives

The Honolulu Board of Water Supply (BWS) manages the drinking water supply and distribution system for the island of Oʻahu, Hawaiʻi, serving approximately one million customers with fifty-four 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 two-thousand miles of pipes and installs approximately thirty miles of pipe annually at an average cost of about $1.6 million per mile. Over the last 22 years the BWS Oʻahu water-distribution system has averaged 366 breaks per year. Given the scale of its operations the BWS needs to develop 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:

a. 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 more scientific manner.

b. 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.

c. 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.

d. Calculate the reliability of the water-distribution system identifying various pipe ages, various pipe diameters, and various pipe types.

e. Undertake availability analysis; apply process-capability analysis to availability.

f. Undertake Bayesian analysis for the probability of failure of a given pipe age, pipe diameter, pipe type, and soil type.

g. Develop a pipe-replacement prioritization.

h. 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 BWS regarding past water-main breaks.

Principal Findings and Significance

1. Concrete cylinder pipes, when compared to composite pipe systems, are relatively inefficient in performance.
2. Concrete cylinder pipes, when compared to other pipes, are expensive and uneconomical to maintain.
3. Though ductile iron pipes produce the maximum defectives from a repair perspective, overall they are 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 the Synopsis

Chung, R.Y.S., S.T. Hata, A.J. Park, R.K. Cundiff, and M.C. Tilker, 2008, Honolulu Board of Water Supply 2007-08 Report http://www.boardofwatersupply.com/cssweb/display.cfm?sid=11630

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 Hawai i

Basic Information

Title:	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 Hawai i
Project Number:	2009HI243B
Start Date:	3/1/2009
End Date:	2/28/2010
Funding Source:	104B
Congressional District:	Hawai`i 1st
Research Category:	Water Quality
Focus Category:	Water Quality, Ecology, Recreation
Descriptors:	Human pathogenic marine vibrio bacteria
Principal Investigators:	Roger Fujioka, Roger Fujioka

Publications

There are no publications.

Introduction

The majority of the currently available information concerning *Vibrio* species is based on studies conducted in temperate regions. Information on the prevalence and ecology of these species in tropical areas, such as Hawai'i, is limited. Four pathogenic *Vibrio* species (*V. alginolyticus, V. cholerae, V. parahaemolyticus,* and *V. vulnificus*) have been documented to cause human infections in Hawai'i.

For example, *V. vulnificus* infections have recently resulted in two deaths related to exposure to coastal waters. One death occurred on Hawai'i Island and the second death occurred on O'ahu. *V. cholerae* infections, due most likely to the consumption of contaminated seafood, have also been documented in Hawai'i. In addition infections of *V. parahaemolyticus* and wound infections due to *V. alginolyticus* have also been reported in Hawai'i. Prior to the present study there have been no studies conducted to determine the prevalence of these pathogens in the coastal waters of Hawai'i. Thus with this study we hope to answer questions concerning the prevalence of pathogenic *Vibrio* species in Hawai'i and their potential public health significance to people using Hawaiian coastal waters for recreational purposes.

The identified problems are: 1) while methods exist to enumerate *Vibrio* spp. from water samples none of these methods have been approved by the United States Environmental Protection Agency (USEPA) to monitor waters for pathogenic *Vibrio* species. Thus there is a need to collect additional data and to identify an appropriate enumeration method; 2) there have been no prior systematic studies to determine concentrations of pathogenic *Vibrio* spp. in various types of Hawaiian coastal waters used by humans; 3) water-quality standards relating to *Vibrio* exposure in recreational waters have been raised—but testing for such exposure 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. to people by the recreational use of various Hawaiian coastal waters.

Problem and Research Objectives

Objective 1: to determine the prevalence of four human pathogenic *Vibrio* species (*V. alginolyticus, V. cholerae, V. parahaemolyticus,* and *V. vulnificus*) in coastal waters approved for recreational use that are characterized by high salinity and negligible impact from land-based run-off compared to coastal waters characterized by variable salinity due to impact by land-based run-off.

Objective 2: to determine the prevalence of these four human pathogenic *Vibrio* species in confined coastal waters, not approved for recreational use, that are characterized by consistent contamination from land-based run-off.

Objective 3: to determine if special conditions of low salinity and warm water temperature (>30°C) present on Hawai'i Island are selective for the growth of these four human pathogenic *Vibrio* species.

Objective 4: to determine the prevalence of these four human pathogenic *Vibrio* species in the sediments of coastal waters as a possible source of these pathogens in the water column.

Objective 5: to determine whether raw sewage, effluent receiving primary treatment, or effluent receiving secondary treatment, when discharged into Hawaiian coastal waters, are possible sources for these four human pathogenic *Vibrio* species.

Methodology

Sample Categories

Sampling sites on the islands of Oʻahu and Hawaiʻi were divided into four water-quality categories based on their use and the impact at each site by land-based run-off.

1. Primary Coastal Beaches Approved for Swimming (Oʻahu): these sites consist of the more popular beaches on Oʻahu and are not impacted by land-based run-off. Thus they can be characterized as having high salinity and low turbidity.
2. Secondary Coastal Beaches Approved for Swimming (Oʻahu): these sites consist of the less popular, but still heavily used, beaches on Oʻahu. They are impacted by land-based run-off and as a result have variable salinities and higher turbidity.
3. Coastal Harbors, Ponds, and Canals Not Approved for Swimming (Oʻahu): these sites are confined coastal bodies that have poor circulation with the open ocean. They are highly susceptible to land-based run-off and as a result have variable salinities and high turbidity. As these sites present obvious pollution problems and are not approved for recreational use such use of these waters is extremely limited. However a case of accidental contact with such waters resulting in infection and death by *V. vulnificus* has occurred.
4. Approved Swimming Sites (Hawaiʻi Island): study sites were selected based on past evidence of *V. vulnificus* wound infection. While beaches on Oʻahu are largely represented by typical sandy swimming beaches many beaches on Hawaiʻi Island differ. As Hawaiʻi Island is geologically much younger than Oʻahu there are fewer sandy beaches such as those seen on Oʻahu. On Hawaiʻi Island many largely rock-enclosed coastal ponds are used for recreation. Many of these sites are, due to land-based run-off, generally susceptible to freshwater input and these coastal ponds are characterized by low and variable salinity.

These distinctions between Hawaiʻi Island and Oʻahu have to do with their differing geologic ages. While Oʻahu is 2–3 million years old Hawaiʻi Island is less than 1 million years old and still forming. The age of the island has an effect on its hydrogeology. Over time sedimentary deposits form a relatively impermeable rock called cap rock. Cap rock is present on Oʻahu but absent on Hawaiʻi Island. As a result, when it rains on Oʻahu the cap rock prevents the groundwater from flowing out into coastal waters and forces it to percolate underground. In contrast, similar cap rock is absent on Hawaiʻi Island where groundwater is able to readily discharge into coastal waters and ponds. In such ponds the salinity of the water is low. This low-salinity condition selects for the growth of *Vibrio* spp. bacteria such as pathogenic *Vibrio* spp. Some coastal ponds are characterized by both low salinity and higher temperatures 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* and the subsequent infection by *V. vulnificus* of swimmers using these ponds.

Sample Collection

At all primary and secondary recreational beaches water samples were collected at waist depth in sterile one-liter plastic sampling bottles. Harbor, canal, and pond sites were sampled

from shore using a sampling bucket and were then similarly collected in sterile one-liter plastic sampling bottles. Sediment samples were taken at knee depth 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 Oʻahu samples were analyzed within three hours of collection.

Water and sediment samples from Hawaiʻi Island were similarly collected into sterile one-liter plastic sampling bottles. Due to transport times to the Oʻahu laboratory, Hawaiʻi Island samples were processed within eight hours of collection.

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

All samples were transported for analysis to the Oʻahu 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 (NTU). 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 specifically. 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 (USGS; 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. After 200 ml of PB was added to each bottle the bottle was shaken by hand for five minutes. After shaking the sediment sample was allowed to settle for thirty seconds and the supernatant was then transferred into a separate sterile bottle. This elution process was done twice for each sediment sample 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

Two biochemical tests were used to make a presumptive identification of the isolates picked off the CV plates. Sucrose fermentation and growth at various levels of salt are both tests accepted by the U.S. Food and Drug Administration Bacterial Analytical Manual (USFDA BAM) for the speciation of *Vibrio* species (DePaola and Kaysner 2004). Sucrose fermentation was conducted on TCBS agar. Isolates from the CV plates were also subjected to salt tolerance tests. Growth of turquoise and mauve colonies were tested at three salt concentrations (0%, 6%, and 8%) and the growth of colorless colonies was tested at four salt concentrations (0%, 6%, 8%, and 10%). Salt tubes were prepared as specified by the USFDA BAM (DePaola and Kaysner 2004). Salt broths were initially prepared by adding appropriate amounts of NaCl to a nutrient broth (NB). No NaCl was added for the 0% broth, 6 g of NaCl per 100 ml of NB was added for the 6% broth, 8 g of NaCl per 100 ml of NB was added for the 8% broth, and 10g of NaCl per 100 ml of NB was added for the 10% broth. Salt broths were placed onto a stir plate with a stir bar and mixed until the NaCl dissolved completely. After mixing 5 ml of each broth was allocated into glass screw-cap tubes and sterilized by autoclaving. A 2% saline broth (2 g NaCl per 100 ml distilled water) was also made and 1 ml was allocated into screw cap tubes and sterilized by autoclaving.

A twenty-four-hour culture of the isolates grown on TSA + 0.5% NaCl was used for biochemical testing. Isolates from TSA + 0.5% NaCl plates were streaked onto TCBS plates using sterile toothpicks and the plates were incubated for twenty-four hours at 35°C. After the incubation period isolates were scored as sucrose positive or sucrose negative. Prior to inoculating the salt tubes, a single colony of each isolate was picked off the TSA + 0.5% NaCl plate and homogenized into a tube of 2% saline broth. A 0.1 ml sample from the saline broth tube was then used to inoculate each of the (0%, 6%, 8%, and 10%) salt tubes. The tubes were incubated at 35°C for seven days and scored as growth being present or absent (Choopun et al. 2002). Based on sucrose fermentation and salt tolerance, isolates were presumptively identified as *V. alginolyticus, V. cholerae, V. parahaemolyticus,* or *V. vulnificus* and then confirmed by PCR.

Extraction of *V. cholerae, V. parahaemolyticus,* and *V. vulnificus* DNA

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 for *V. cholerae, V. parahaemolyticus,* and *V. vulnificus* were used to confirm presumptive isolates from all samples.

Confirmation of Presumptive Isolates Using Species-Specific PCR Primers

Table 1 is a list of the specific primers that were used for each species. Presumptive *V. cholerae* isolates were confirmed by primers developed by Chun et al. (1999) These primers

target the intergenic spacer regions (ISR) between the 16S and 23S rDNA. These regions are thought to be under less evolutionary pressure than rRNA coding regions and thus can be used to differentiate between closely related organisms. These primers were shown to be able to differentiate between the two closely related species *V. cholerae* and *V. mimicus*. The protocol for PCR amplification described by Chun et al. (1999) was followed and the resulting PCR product was visualized on a 1.5% agarose gel.

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

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

For confirmation of presumptive *V. vulnificus* isolates, primers developed by Kim and Jeong were used. By analysis of known 16S rRNA sequences of *Vibrio* species, four variable regions were identified that were used as target sequences for primers specific for the amplification of 16S rRNA genes of *V. vulnificus*. As 16S rRNA genes are essential constituents of all living organisms there is no problem with the gene loss which may be a possibility with hemolysin/cytolysin genes. In addition, 16S rRNA genes are present in high copy numbers within cells. The protocol for PCR amplification described by Kim and Jeong (2001) was followed and the resulting PCR product was visualized on a 1.5% agarose gel.

PCR confirmation of presumptive *V. parahaemolyticus* isolates relied on primers developed by Lee et al. (1995). Because environmental strains of *V. parahaemolyticus* generally do not produce hemolysins and most clinical or pathogenic strains do, hemolysin genes are sometimes used as genetic markers to characterize pathogenic *V. parahaemolyticus*. For this study a more reliable genetic marker, as developed by Lee et al. (1995), was used. This genetic marker is a fragment on the chromosomal DNA of *V. parahaemolyticus* named pR72H. The function of this region of DNA is unknown but it was shown to be conserved among all *V. parahaemolyticus* strains. The protocol for PCR amplification described by Lee et al. (1995) was followed for PCR amplification and the resulting PCR product was visualized on a 1.5% agarose gel.

Principal Findings and Significance

The first objective of this study was to determine the prevalence of *V. alginolyticus, V. cholerae, V. parahaemolyticus,* and *V. vulnificus* in coastal waters with high salinity and negligible impact from land-based run-off compared to coastal waters that have variable salinity due to impact by land-based run-off.

Given prior data gathered from studies conducted in temperate areas we hypothesized that because pathogenic *Vibrio* species are known to prefer lower salinity for growth we would expect them to be present in low-salinity waters that are impacted by land-based run-off. We found this to be true in the cases of *V. parahaemolyticus* and *V. vulnificus*. These two species were prevalent in low-salinity sites that were impacted by land-based run-off but not detectable in high-salinity coastal waters which were not impacted by land-based run-off.

In contrast *V. alginolyticus* was prevalent at all sites regardless of salinity. Though this species is generally associated with high-salinity waters, nutrients brought in by land-based run-off overcame salinity barriers and stimulated *Vibrio* species growth. Furthermore *V. parahaemolyticus* and *V. vulnificus* were prevalent in low-salinity swimming ponds on Hawai'i Island, indicating once again that salinity has a strong influence on the prevalence of these two species. *V. cholerae* was not recovered in either impacted or non-impacted sites. *V. cholerae* is known to prefer very-low-salinity waters. However environmental strains of *V. cholerae* have been recovered from coastal waters in temperate climates when an initial enrichment step was used to increase the chance for detection. Pre-enrichment of samples was not done in this study because we wanted to determine the concentration in natural coastal waters. Thus this species may have been present but at levels below the detection limit of our assay. In addition *V. cholerae* has been found in close association with chitinous organisms such as zooplankton. Studies have shown that this association is used by *V. cholerae* during times of environmental stress (e.g., low water temperature). Therefore it may be possible that because these sites had salinities above those which are normally tolerable by *V. cholerae* they may be more likely to be attached to zooplankton than free in the water column. Thus, based on our data, we can conclude that our hypothesis was valid and that *V. parahaemolyticus* and *V. vulnificus* are more prevalent in low-salinity coastal waters that are impacted by land-based run-off.

The second objective of this phase was to determine the prevalence of the four pathogens in confined coastal waters such as harbors, canals, and ponds not approved for swimming. We hypothesized that because such sites are not flushed by clean ocean waters they would contain elevated nutrients and have lowered salinity—conditions favorable for the growth of *Vibrio* species. Data from this study indicate that *V. alginolyticus*, *V. parahaemolyticus,* and *V. vulnificus* were prevalent at such sites—similar to the prevalence of these organisms at beaches that are impacted by land-based run-off and have low-salinity. *V. vulnificus* was not recovered from any of the harbor sites. This may be explained by the high salinity (34 ppt) present at these sites. Also *V. cholerae* was not recovered from any of the sampling sites. Thus we can conclude that our hypothesis was valid and that primarily *V. parahaemolyticus* and *V. vulnificus* were prevalent in these low-salinity coastal waters having poor exchange of open-ocean water.

The third objective of this phase of the study was to determine if the special conditions of low salinity and warmer water temperatures (>30°C) present in certain recreational waters on Hawai'i Island are selective for the growth of the four human pathogenic *Vibrio* species. We hypothesized that because these conditions are known to favor the growth of pathogenic *Vibrio* species we would expect them to be present in the thermally heated ponds present on Hawai'i Island. We found that though overall counts of bacteria were lower in these ponds as compared to non-thermally heated ponds, *V. alginolyticus*, *V. parahaemolyticus,* and *V. vulnificus* were prevalent in such ponds. Thus we conclude that our hypothesis was valid and that warmer water temperatures and low salinity can select for these three *Vibrio* pathogens. Furthermore there has been past evidence of infection and at least one human death from *V. vulnificus* associated with the use of these ponds. Thus *Vibrio* pathogens recovered from these thermally heated ponds may potentially be more virulent as such pathogens have successfully adapted for survival at temperatures very similar to the temperatures of the human body.

The fourth objective of this study was to determine the prevalence of the four human pathogenic *Vibrio* species in the sediment biofilm of coastal waters and evaluate such a

possible presence as a source of these pathogens in the water column above. Data from this study showed that the prevalence of pathogenic *Vibrio* species in coastal sediments demonstrated 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. Such sites have lower salinity and are influenced by land-based run-off and *V. parahaemolyticus* and *V. vulnificus* were also prevalent in the water columns at these types of sites. Based on data from this study it is apparent that sediments below secondary coastal waters can serve as a source of pathogenic *Vibrio* species identified in the water column.

The fifth and final objective of this study was to determine whether raw sewage, effluent receiving primary treatment, or effluent receiving secondary treatment can serve as possible sources of the four human pathogenic *Vibrio* species. Data from this study 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. Based on this data it is apparent that sporadic shedding of *V. parahaemolyticus* and *V. vulnificus* is occurring within the population while *V. cholerae* is being consistently shed by asymptomatic carriers. The low salinity of wastewater favors growth of *V. cholerae*. Accidental release of raw sewage can introduce these pathogens into coastal waters—which may lead to public health consequences for the users of such waters.

Publications Cited in the Synopsis

Azanza, P.V., K.A. Buckle, and G.H. Fleet, 1996, "Effect of diluents on the enumeration of *Vibrio vulnificus,*" *International Journal of Food Microbiology* 30:385–390.

Choopun, N., V. Louis, A. Huq, and R.R. Colwell, 2002, "Simple procedure for rapid identification of *Vibrio cholerae* from the aquatic environment," *Applied and Environmental Microbiology* 68 (2): 995–998.

Chun, J., A. Huq, and R.R. Colwell, 1999, "Analysis of 16S-23S rRNA intergenic spacer regions of *Vibrio cholerae* and *Vibrio mimicus,*" *Applied and Environmental Microbiology* 65 (5): 2202–2208.

DePaola, A., and C.A. Kaysner, 2004, "Vibrio [Online]," *Bacterial Analytical Manual online.* Rockville, MD: United States Food and Drug Administration, http://www.cfsan.fda.gov/~ebam/bam-9.html.

Kim, M.S., and H.D. Jeong, 2001, "Development of 16S rRNA targeted PCR methods for the detection and differentiation of *Vibrio vulnificus* in marine environments," *Aquaculture* 193:199–211.

Lee, C.Y., S.F. Pan, and C.H. Chen, 1995, "Sequence of a cloned pR72H fragment and its use for detection of *Vibrio parahaemolyticus* in shellfish with the PCR," *Applied and Environmental Microbiology* 61 (4): 1311–1317.

Lee, J.W., I.J. Jun, H.J. Kwun, K.L. Jang, and J. Cha, 2004, "Direct identification of *Vibrio vulnificus* by PCR targeting elastase gene," *Journal of Microbiology and Biotechnology* 14 (2): 284–289.

Myers, D.N., D.M. Stoeckel, R.N. Bushon, D.S. Francy, and A.M.G. Brady, 2003, "Fecal Indicator Bacteria," in *National Field Manual for the Collection of Water-Quality Data,* D.N. Myers and F.D. Wilde (eds.), United States Geological Survey, http://water.usgs.gov/owq/FieldManual/index.html.

Optimal Groundwater Extraction and Water Recycling

Basic Information

Title:	Optimal Groundwater Extraction and Water Recycling
Project Number:	2009HI254B
Start Date:	3/1/2009
End Date:	2/28/2010
Funding Source:	104B
Congressional District:	Hawai`i 1st
Research Category:	Social Sciences
Focus Category:	Economics, Management and Planning, Hydrology
Descriptors:	Water Demand Management, Efficiency Pricing, Water Recycling, Water Treatment, Dynamic Optimization, Welfare, Marginal User Cost
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 Hawai i at Mânoa 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.

Presentations Resulting from the Research Project

Pongkijvorasin, Sittidaj, James A. Roumasset, and Christopher Wada, "Confuser Cost, Stock-to-Stock Externalities and Ordering the Extraction of Renewable Resources," University of Hawai'i at Mānoa Department of Economics, Applied Microeconomics Workshop, October 28, 2009.

Pongkijvorasin, Sittidaj, James A. Roumasset, and Christopher Wada, "Confuser Cost, Stock-to-Stock Externalities and Ordering the Extraction of Renewable Resources," University of Alberta Energy and Environmental Economics Seminar Series, Canada, October 30, 2009.

Roumasset, James A., and Christopher Wada, "Beyond Sustainable Yield: Managing Multiple Aquifers, Recycling, and Watershed Conservation in the South O'ahu Aquifer System," University of Hawai'i at Mānoa Water Resources Research Center, March 5, 2010.

Grant Proposals Resulting from the Research Project

Bruland, Gregory, Kimberly Burnett, Gretchen Daily, Henrieta Dulaiova, Lee H. Endress, Thomas Giambelluca, Craig Glenn, Alexander C. McLain, James A. Roumasset, and Nori Tarui, "Sustainable Science for Watershed Management: A Mountain-to-Sea Assessment of Mānoa Watershed," University of Hawai'i Sustainability Grant Competition, 2009 (not funded).

Burnett, Kimberly, Thomas Giambelluca, and James A. Roumasset, "Sustainable Science for Watershed Management: A Mountain-to-Sea Assessment of Mānoa Watershed," National Science Foundation Urban Long-Term Research Area (ULTRA) Exploratory Award, 2009 (not funded).

Burnett, Kimberly, Thomas Giambelluca, James A. Roumasset (PI), and Oliver Timm, "Adapting Water and Watershed Management to Climate Change in a Hydrological Basin," National Science Foundation, $1,499,956, 2010–2014 (pending).

Roumasset, James A., and Aly El-Kadi (Co-PIs), "Increasing Water Availability Through Groundwater Alternatives: Multiple Sources, Water Recycling and Desalination," U.S. Geological Survey via the University of Hawai'i at Mānoa Water Resources Research Center, $356,713, January 2011–December 2012 (pending).

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 Oʻahu (Hawaiʻi), 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.

$$(1) \qquad \underset{q_t^{GH},q_t^{BH},q_t^{GO},q_t^{RO},q_t^{BO}}{Max} \int_0^\infty e^{-\delta t} \left\{ \begin{array}{l} \int_0^{q_t^{GH}+q_t^{BH}} D_H^{-1}(x,t)dx + \int_0^{q_t^{GO}+q_t^{RO}+q_t^{BO}} D_O^{-1}(x,t)dx - \\ (q_t^{GH}+q_t^{GO})c_G(h_t) - (q_t^{BH}+q_t^{BO})c_B - q_t^{RO}c_R \end{array} \right\} dt$$

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

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

$$(2) \qquad \begin{array}{l} p_t^H = \min\{c_G(h_t) + \lambda_t, c_B\} \\ p_t^O = \min\{c_G(h_t) + \lambda_t, c_R, c_B\} \end{array}$$

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.

Empirical Results

In an application to the Pearl Harbor aquifer and consumption district on the island of O'ahu, Hawai'i, 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.

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	

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

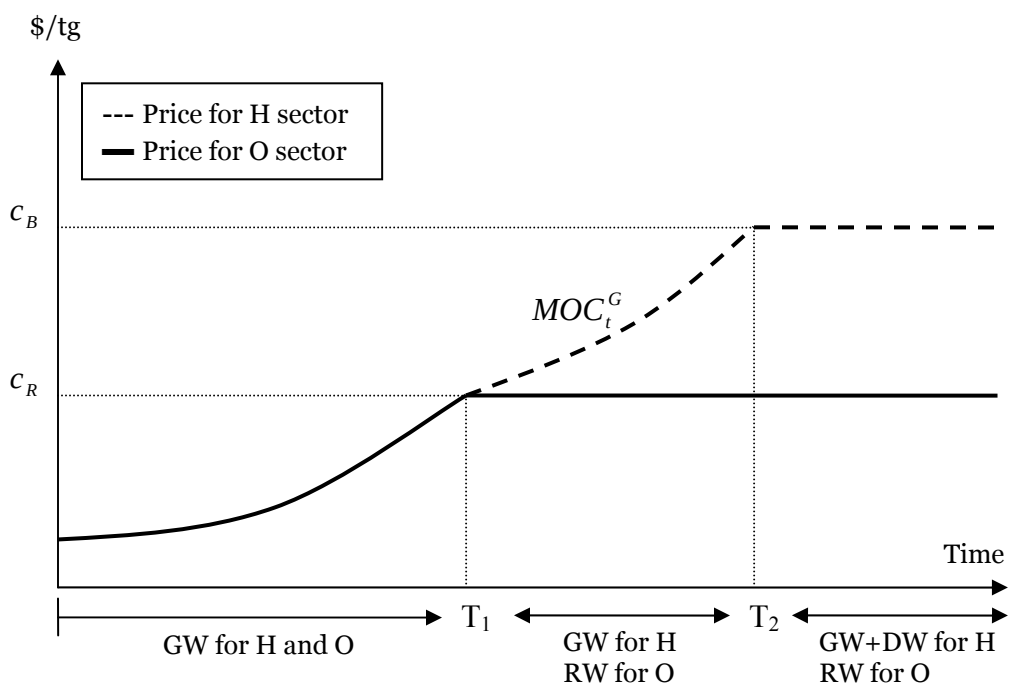

Figure 1. Hypothetical MOC paths for scenario A

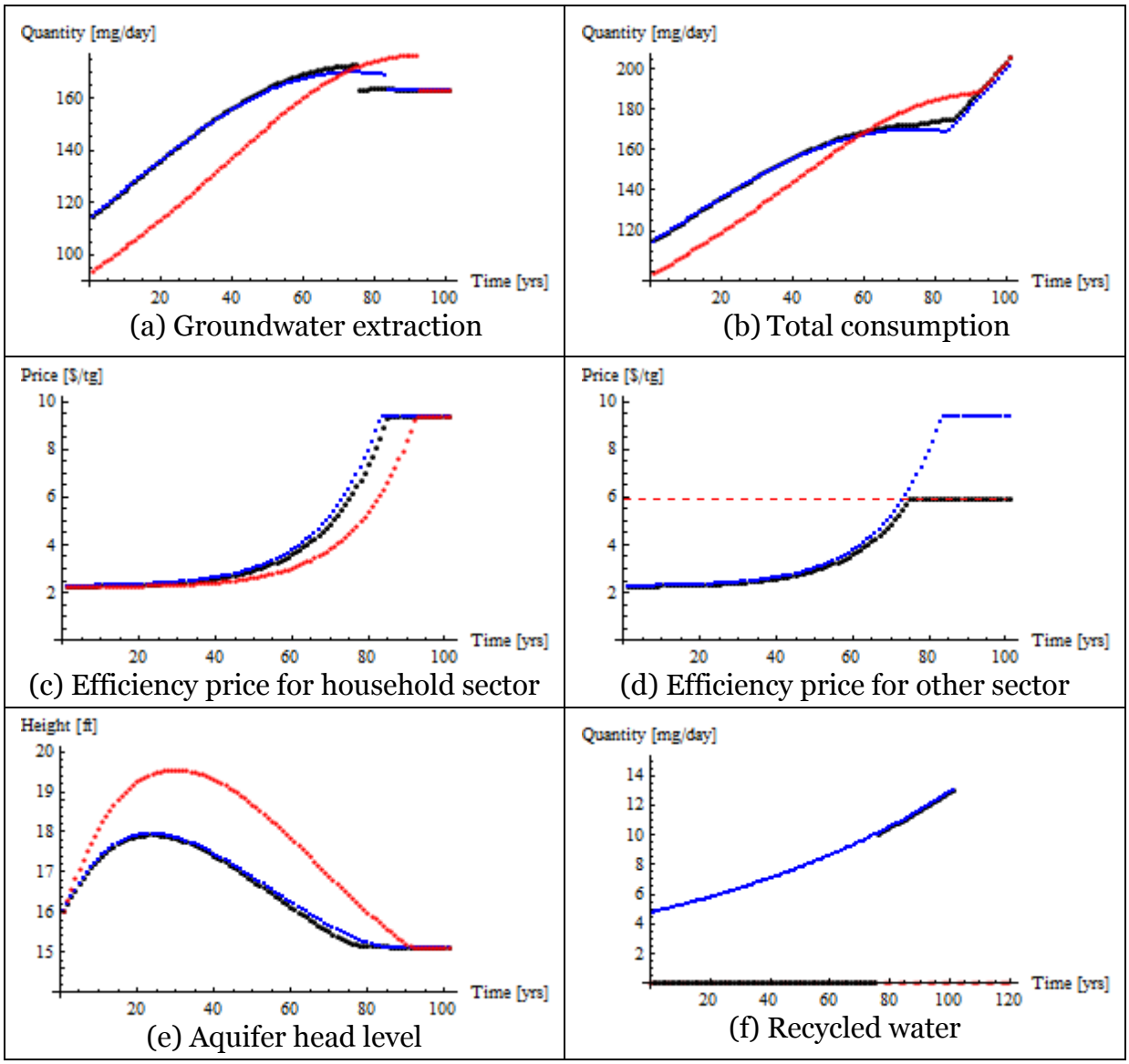

Figure 2. Various time paths for three recycling scenarios:
optimal (black), none (blue), premature (red)

Publications Cited in Synopsis

Draper, A.J., M.W. Jenkins, K.W. Kirby, J.R. Lund, and R.E. Howitt, 2003, "Economic-Engineering Optimization for California Water Management," *Journal of Water Resources Planning and Management* 129 (3): 155–164.

Jenkins, M.W., A.J. Draper, J.R. Lund, R.E. Howitt, S. Tanaka, R. Ritzema, G. Marques, S.M. Msangi, B.D. Newlin, B.J. Van Lienden, M.D. Davis, and K.B. Ward, 2001, Improving California water management: Optimizing value and flexibility. Davis, CA.: University of California, Davis, Center for Environmental and Water Resources Engineering, available online at: http://cee.engr.ucdavis.edu/faculty/lund/CALVIN.

Jenkins, M.W., J.R. Lund, R.E. Howitt, A.J. Draper, S.M. Msangi, S.K. Tanaka, R.S. Ritzema, and G.F. Marques, 2004, "Optimization of California's Water Supply System: Results and Insights," *Journal of Water Resources Planning and Management* 130 (4): 271–280.

Wilkinson, R., and D.G. Groves, 2006, *Rethinking Water Policy Opportunities in Southern California: An Evaluation of Current Plans, Future Uncertainty, and Local Resource Potential.* Santa Barbara, CA: University of California, Santa Barbara, Water Policy Program.

Wilson Okamoto Corporation, 2008, *Hawaii Water Plan: Water Resource Protection Plan.* Prepared for the State of Hawaii Commission of Water Resource Management.

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:	7/31/2010
Funding Source:	Other
Congressional District:	Hawai i 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

Publication

1. A final report will be published in the U.S. Geological Survey Scientific Investigations Report series.

Introduction

The Pearl Harbor aquifer is the most important aquifer on the island of Oʻahu and currently supplies about 100 million gallons per day of fresh groundwater mainly for public use. Decisions related to future infrastructure development and alternate sources of fresh water, 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 Hawaiʻi 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 Oʻahu, 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 Hawaiʻi.

Publications Resulting from the Research Project

A final report will be published in the U.S. Geological Survey Scientific Investigations Report series.

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 million gallons per day 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.

Publications Cited in the Synopsis

Gingerich, S.B., 2008, *Ground-water availability in the Wailuku area, Maui, Hawai'i,* U.S. Geological Survey Scientific Investigations Report 2008-5236, 95 p.

Langevin, C.D., D.T. Thorne Jr., A.M. Dausman, M.C. Sukop, and W. Guo, 2007, *SEAWAT Version 4: A Computer Program for Simulation of Multi-Species Solute and Heat Transport* in U.S. Geological Survey Techniques and Methods Book 6, Chapter A22, pp. i–vi, 1–39.

Oki, D.S., 2005, *Numerical Simulation of the Effects of Low-Permeability Valley-Fill Barriers and the Redistribution of Ground-Water Withdrawals in the Pearl Harbor Area, Oahu, Hawaii,* U.S. Geological Survey Scientific Investigations Report 2005-5253, 111 p.

Oki, D.S., W.R. Souza, E.L. Bolke, and G.R. Bauer, 1998, "Numerical analysis of the hydrogeologic controls in a layered coastal aquifer system, Oahu, Hawaii, USA," *Hydrogeology Journal,* 6:2, 243–263.

Paillet, F.L., and A.E. Hess, 1995, *Geophysical log data from basalt aquifers near Waipahu on the Island of Oahu and Pahoa on the island of Hawaii, Hawaii,* U.S. Geological Survey Open-File Report 95-383, 62 p.

Paillet, F.L., J.H. Williams, D.S. Oki, and K.D. Knutson, 2002, "Comparison of formation and fluid-column logs in a heterogeneous basalt aquifer," *Ground Water,* 40:6, 577–585.

Rotzoll, K., 2010, *Effects of groundwater withdrawal on borehole flow and salinity measured in deep monitor wells in Hawaii—implications for groundwater management,* U.S. Geological Survey Scientific Investigations Report 2010–5058.

Shalev, E., A. Lazar, S. Wollman, S. Kington, Y. Yechieli, and H. Gvirtzman, 2009, "Biased monitoring of fresh water-salt water mixing zone in coastal aquifers," *Ground Water,* 47:1, 49–56.

Souza, W.R., and C.I. Voss, 1987, “Analysis of an anisotropic coastal aquifer system using variable-density flow and solute transport simulation,” *Journal of Hydrology*, 92:1, 17–41.

Publications from Prior Projects

Rotzoll, K., 2010, *Effects of groundwater withdrawal on borehole flow and salinity measured in deep monitor wells in Hawaii—implications for groundwater management*, U.S. Geological Survey Scientific Investigations Report 2010–5058.

Rotzoll, K., D.S. Oki, and A.I. El-Kadi, 2010, “Changes of freshwater-lens thickness in basaltic islands aquifers overlain by thick coastal sediments,” *Hydrogeology Journal*, DOI: 10.1007/s10040-010-0602-4.

Information Transfer Program Introduction

None.

Technology Transfer

Basic Information

Title:	Technology Transfer
Project Number:	2009HI259B
Start Date:	3/1/2009
End Date:	2/28/2010
Funding Source:	104B
Congressional District:	Hawai`i 1st
Research Category:	Not Applicable
Focus Category:	Education, Water Use, Water Supply
Descriptors:	Technology transfer, Outreach, Information dissemination
Principal Investigators:	Philip Moravcik, Philip Moravcik

Publications

1. Moravcik, Philip, 2009 (February), Water Resources Research Center Bulletin, University of Hawai i at Mânoa Water Resources Research Center, 4 pp.
2. Moravcik, Philip, 2009 (July), Water Resources Research Center Bulletin, University of Hawai i at Mânoa Water Resources Research Center, 8 pp.

Introduction

Hawai‘i, being one of the nation’s less populous states, provides many opportunities for water researchers to directly interact with senior government administrators and policy makers. To further the goal of broadening the knowledge and appreciation of Hawai‘i’s water resources, the Technology Transfer Program of the University of Hawai‘i at Mānoa (UHM) Water Resources Research Center (WRRC) organizes conferences, meetings, workshops, and biweekly seminars; produces newsletters; produces posters and other materials for presentations; and maintains the WRRC website. The program principal investigator (PI) meets with county, state, and federal agency personnel regarding water-resource issues and assists with proposal writing, research-project implementation, and report authorship for WRRC’s research projects.

Technology Problem and Research Objectives

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

Methodology

WRRC Bulletins; other publications; the WRRC website; and conferences, meetings, workshops, and biweekly seminars all serve to aid WRRC 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 WRRC website.

During the current reporting period the Technology Transfer Program produced two bulletins describing research projects and center activities and news. During this reporting period the Technology Transfer Program PI also made extensive use of the center’s large-format printer/plotter—producing posters for display at local, national, and international meetings and conferences. Two of these posters, illustrating the work of graduate-student researchers, won awards at conferences.

The Technology Transfer Program organizes 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 coordinate the seminars 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 current reporting period.

Spring Semester 2009 Seminar Coordinator: Dr. Aly El-Kadi

Mar. 5	John Hughes, Jr.	Chevron Environmental Management Company and UHM Department of Geology and Geophysics Graduate Research Assistant	Measuring Light Non-Aqueous Phase Liquids (e.g., Gasoline) Flux in a Tidal Setting
Mar. 13	James Juvik	University of Hawai‘i at Hilo Department of Geography & Environmental Science	Homage to Ekern: A 50th Anniversary Reassessment of the Seminal “Lana‘i Fog-drip Study”
Mar. 19	Kolja Rotzoll	United States Geological Survey, Honolulu, Hawai‘i	Can we Trust Salinity Profiles from Deep Monitoring Wells in Hawai‘i?
Apr. 2	Sanjit Deb	UHM Department of Natural Resources and Environmental Management Post Doctoral Researcher	Susceptibility Assessment of Shallow Landslides on O‘ahu, Hawai‘i
Apr. 15	Jon Stock	United States Geological Survey, Honolulu, Hawai‘i	Estimating Sediment Transport from Ridge to Reef
Apr. 24	Mirabbos Hojamberdiev	Uzbekistan Academy of Sciences Institute of General and Inorganic Chemistry Ph.D.	Sustainable Development and the Environment in Uzbekistan
Apr. 30	P. Suresh C. Rao	Purdue University School of Civil Engineering Lee A. Rieth Distinguished Professor of Civil Engineering and Agronomy	Nutrient Load-Discharge Relationships Across Scales in Engineered Catchments: Order Out of Complexity

Fall Semester 2009 Seminar Coordinator: Dr. John Cusick

Sept. 18	Eugene Dashiell	Environmental Planning Services Consulting Environmental Planner	Problems with National Watershed Planning Policy
Oct. 23	Anthony Kuh	UHM Department of Electrical Engineering Professor and Department Chair	Renewable Energy and Island Sustainability (REIS) program
Nov. 6	Mark Ingoglia	Pacific Air Forces Natural Infrastructure (Environmental) Branch Chief	Sustainable Solutions in the Pacific: US Air Force Environmental Management
Nov. 20	Douglas A. Codiga, Esq.	Schlack Ito Lockwood Piper & Elkind Attorney	Hawai'i Clean Energy Law and Policy
Dec. 4	Thomas A. Schroeder	UHM Joint Institute for Marine and Atmospheric Research Director	Hurricane Risk Modeling: "Beyond the 100-year Rain/Flood"

Spring Semester 2010 Seminar Coordinator: Dr. Clark Liu

Jan. 22	Clark Liu	UHM Civil and Environmental Engineering and WRRC	Water and energy sustainability in a changing environment: An Introduction
Feb. 5	Roger Babcock	UHM Civil and Environmental Engineering and WRRC	Island water sustainability: Wastewater treatment, disposal, recycling
Feb. 19	Paul Bishop	National Science Foundation Environmental Engineering Program Director	The Water-Energy Nexus and NSF Research

WRRC Website

The WRRC website <www.wrrc.hawaii.edu> is continually updated with new information concerning WRRC researchers' activities, grant announcements, meetings, reports, and seminars as well as information concerning the WRRC L. Stephen Lau Scholarship Fund. The website also provides information about WRRC facilities and personnel.

Of particular significance is the listing of WRRC publications on the website. Full-text PDF files of our earlier research reports, which were published in-house, are available through an arrangement with the University of Hawai'i's ScholarSpace digital repository

program. Currently WRRC researchers generally publish their research in peer-reviewed journals. Such publication most often imposes copyright restrictions on re-publication through full-text postings—however we continue to post abstracts and publication data for these contemporary articles.

Poster Production

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

USGS Summer Intern Program

None.

Notable Awards and Achievements

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

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 â¤½Solar Energy Driven Humidification-Dehumidification Seawater Desalination Systems.â¤ The project runs from 1 April 2009 to 31 December 2009. Our research team will collaborate with a local technology company to design, construct, and test a laboratory-scale prototype HDH desalination system.