Water Resources Research Center
Annual Technical Report
FY 2008

Introduction

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University of Hawai‘i

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The earliest systematic and comprehensive scientific investigation of the world’s oceans was carried out between 1872 and 1876 by a British expedition using the refitted warship H.M.S. Challenger. One of the many ocean-bottom samples taken on this epic voyage came from a location off the southern shore of the island of O‘ahu, in what was then the Kingdom of Hawai‘i.

Over the ensuing century or so Honolulu, located on the southern shore of the island of O‘ahu, became a fairly large city (metropolitan population of ca. one million). Honolulu encountered many of the same issues faced by other similar-size cities, including sewage disposal. By the late 1970s the city was treating its wastewater to “primary” levels and had built two deep-ocean outfalls to disperse the treated effluent into fast-moving ocean currents. The outfall pipes extend roughly 2750 m (9000 feet) offshore with diffuser ports at depths of 67–73 m (220–240 feet). One of these pipes, as it happens, ends very near the location from which the Challenger took its benthic sample in 1875.

The University of Hawai‘i Water Resources Research Center has been involved with monitoring the water and benthos in the area of Honolulu’s treated-effluent outfalls since before the outfalls were built. The monitoring team included the late UH Zoology Professor and WRRC Researcher Dr. E. Alison Kay.

Among numerous other significant publications, Professor Kay authored the definitive book on Hawai‘i shells. In the 1990s she spent a part of each summer in Britain pursuing malacology, her specialty, at British scientific institutions. Working in the British Museum one such summer Dr. Kay uncovered a reference to the O‘ahu benthic sample taken by Challenger scientists more than a century earlier.

Gaining access from the British Museum to study that century-plus-old sample, Professor Kay carefully identified and counted the micromollusks it contained. Remarkably, the species she found in the Challenger sample were virtually the same, in numbers and diversity, as those she was seeing more than one hundred years later in her contemporary samples taken near the treated-effluent outfall pipe–despite more than a quarter-century of treated effluent being dispersed near that location. This clearly demonstrated that twenty-five years of deep-water dispersal of Honolulu’s treated effluent had had no appreciable effect on nearby benthic mollusks.

The discharge monitoring program has been a major element of WRRC activities over the past twenty-five or more years. In addition to researchers carrying on the study of Professor Kay’s mollusks, others study benthic crustaceans and polychaetes. Ecologists work with both scuba gear in the shallower depths and remotely-operated-vehicles carrying video cameras into greater depths to examine fish populations and coral growth. A histopathologist examines captured fish for any signs of toxicity. None of these studies has ever identified any significant effects from the deep-water dispersal of Honolulu's treated effluent.

The alternative to Honolulu's current discharge system would require roughly one billion dollars to upgrade on-island treatment facilities to "secondary" processing. Based upon WRRC's and other's monitoring results, this one-billion-dollar expenditure would gain nothing in improved water quality for human use or in any benefit for marine biota.

On the other hand, Honolulu could productively spend roughly one billion dollars on rebuilding its outdated, leaky, and somewhat failure-prone sewage-collection infrastructure and significantly improve the long-term health conditions on the island of O‘ahu

As with the effluent-discharge-monitoring program, the University of Hawai‘i Water Resources Research Center continues to serve as the focal point for organizing UH faculty expertise to study the adequacy, integrity, and purity of Hawai‘i's onshore potable-water resources and to ensure their efficient use. 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 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.

Though modest in size, grants provided through the USGS Water Resources Research Institute Program establish a foundation on which other activities of the Hawaii WRRC are built.

Research Program Introduction

The Hawai‘i 104B program for FY 2008 funded four new research projects and two small allocations for technology transfer and administration. The four new research projects include:

- an investigation of the contribution of forest cover to the capture of rainwater
- a model of a desalination process using humidification-dehumidification powered by solar energy
- a study of the relationship between biodiversity and the trophic status of a local reservoir
- construction of an integrated hydrologic-economic model using optimal control mathematics to enhance management of multiple interconnected groundwater aquifers.

The technology-transfer project funds conferences, seminars, workshops, and newsletters. A like amount went to the administration program, primarily funding faculty travel. Given Hawai‘i’s isolated location, this is a critically important function.

Additional work was completed on a 104G award with an August 31, 2008, end date and continued on a series of projects in cooperation with the Honolulu-headquartered USGS Pacific Islands Water Science Center. WRRC researchers also completed, under no-cost extensions, several projects begun with previous years’ 104B appropriations and pursued many other avenues of research funded by city and county, state, and federal agencies and private firms. All told, non-WRRIP externally-funded projects accounted for over $12 for each $1 from the WRRIP program and university funds added another nearly $9 for each WRRIP dollar.

To provide adequate funding for the four rather modest research projects we have supplemented the 104B funds with university funds. In the future, as salaries and other costs continue to increase, it will be necessary to fund fewer projects or to rethink the type of grants made under this program: partial, rather than full, research associate support; less ambitious projects; or perhaps more community outreach and less actual research.

Coastal Groundwater Management in the Presence of Positive Stock Externalities

Basic Information

Title:	Coastal Groundwater Management in the Presence of Positive Stock Externalities
Project Number:	2005HI125G
Start Date:	9/1/2005
End Date:	8/31/2008
Funding Source:	104G
Congressional District:	Hawaii 1st
Research Category:	Social Sciences
Focus Category:	Economics, Hydrology, Ecology
Descriptors:	groundwater management, marine ecology, dynamic optimization, safeminimum standard, sustainability science
Principal Investigators:	James A. Roumasset, Kaeo Duarte

Publication

1. Pongkijvorasin, Sittidaj, and James Roumasset. 2007. "Optimal conjunctive use of surface and groundwater with recharge and return flows: Dynamic and spatial patterns." *Review of Agricultural Economics* 29(3), pp. 531-539.

Problem and Research Objectives

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

Thus our research objective was to determine the optimal management scheme in Hawai'i for groundwater resources—taking into consideration both the benefits of water consumption and the environmental consequences of freshwater extraction.

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

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

Methodology

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

Bio-hydro-economic Model

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

Mathematically, the problem is to

$$\max_{q_t,b_t}\int_0^{\infty} e^{-rt}\left[\int_0^{q_t+b_t} p(x)dx+\int_0^{m_t} p_m(y)dy-c(h_t)q_t-\bar{p}b_t-c_m(S_t)m_t\right]dt$$

subject to $\dot{h}_t = a[R-l(h_t)-q_t]$

$\dot{S}_t = g(S_t,h_t)-m_t$

where the social surplus is defined as the consumer surplus associated with water and *G. coronopifolia* consumption (the first two terms) less the producer costs of freshwater extraction and ocean-water desalination as well as the cost of harvesting *G. coronopifolia* (the last three terms). The aquifer-head level evolves over time according to changes in natural inflow, leakage, and extraction. The evolution of the *G. coronopifolia* stock depends on harvesting and on the resource's intrinsic growth function (which is itself dependent on the stock and on freshwater discharge).

Manipulation of the first-order conditions for this problem yields the following expression for price:

$$p = c(h)+\frac{\dot{p}-a(R-l(h))c'(h)}{r+al'(h)}+\frac{ag_h(S,h)\theta}{r+al'(h)}$$

The usual expression for the efficient price of a renewable resource includes the first two terms on the right hand side of the equation; price is equal to extraction cost plus marginal user cost. There is a third term, however, when a stock externality exists. In this case the term captures how the stock of groundwater (and hence discharge) affects the growth rate of *G. coronopifolia*.

Freshwater-carried nutrients and algae growth

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

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

Principal Findings and Significance

Native algae growth and nutrients

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

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

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

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

Bio-hydro-economic Model

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

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

We address cultural and ecological value by imposing a “safe-minimum standard” on the *G. coronopifolia* stock in the second approach. When a stock constraint is imposed, the optimal paths of water extraction, aquifer-head level, and price for water are non-monotonic. The aquifer is optimally depleted below its steady-state level initially and is then built back up to the steady-state level in the period that follows. This contrasts with conventional management according to maximum sustainable yield. While the backstop technology (desalination) is never required in the market value scenario (due to the assumption of a stationary demand function), it is implemented for all stock constraints that meet or exceed 75% of the current stock. Maintaining a tight stock constraint requires substantial water conservation—which could be implemented by higher consumer prices at the margin.

The growth function of the stock of *limu* is difficult to estimate in situations where the stock is small relative to its size without predators. Thus in the third approach, we impose a constraint on the intrinsic growth rate, equivalently, a constraint on the salinity level achieved by a minimum discharge level. This minimum discharge is associated with a particular head level, so the constraint is ultimately imposed on the head level of the aquifer. For head constraints that represent a reasonable range of growth rates given the ocean salinity at the study site (1.8%–2%), the optimal approach paths for head, pumping, and price are monotonic. The head level rises over time in all scenarios as the optimal rate of extraction declines over time. With the growth constraints, desalination is never used. Again, the stricter the constraint, the more water conservation is required.

Publications Cited in the Synopsis

Krulce, D.L., J.A. Roumasset, and T. Wilson. 1997. Optimal management of a renewable and replaceable resource: The case of coastal groundwater. *American Journal of Agricultural Economics* 79 (4): 1218–1228.

Hydrologic Analysis of Hawaii Watersheds for Flood Control and Water Quality Management

Basic Information

Title:	Hydrologic Analysis of Hawaii Watersheds for Flood Control and Water Quality Management
Project Number:	2006HI144B
Start Date:	3/1/2006
End Date:	8/31/2008
Funding Source:	104B
Congressional District:	Hawaii 1st
Research Category:	Climate and Hydrologic Processes
Focus Category:	Hydrology, Floods, Non Point Pollution
Descriptors:	Watershed hydrograph, Flood, TMDL
Principal Investigators:	Clark Liu

Publication

1. Liu, C.C.K., and K. Fernandes. 2009. Linear Systems Modeling of Watershed Hydrology and Sediment Transport, to be presented to the 3rd IWA-ASPIRE Conference, International Water Association (IWA), October 18–22, 2009, Taipei, Taiwan

Problem and Research Objectives

The establishment of the rainfall-runoff relationship of a watershed is an important and difficult problem in applied hydrology. The rainfall-runoff relationships of Hawai‘i watersheds are even more difficult to establish than most because Hawai‘i watersheds tend to have steep slopes, small drainage areas, and a high infiltration rate. Currently the simple *rational formula* is used for urban drainage design in Hawai‘i and the more sophisticated *unit-hydrograph method* is used for the design of large flood-control facilities.

The unit-hydrograph method is based on linear systems theory (Dooge 1973). The system impulse response function of a linear system describes the overall system characteristics which affect the input-output relationship. The determination of the system response function of a particular system is called system identification. By the unit-hydrograph method a watershed is taken as a linear system. Its input function is effective rainfall, its output function is direct runoff, and its system response function is called instantaneous unit hydrograph (IUH), which is the direct runoff generated by the watershed system when it receive an input of unit-pulse-effective rainfall. After the IUH of a watershed is identified, direct runoff generated by future rainstorms in the watershed can be calculated by a convolution integration of IUH and rainfall input.

Similarly for waste-loading simulation, the impulse-response function can be called the instantaneous pollutograph (IPG), which is the temporal variation of pollutant concentration at the watershed outlet generated by the watershed system when it receives an input of unit-pulse-effective rainfall. The waste loading at the watershed outlet can then be readily calculated as a product of direct runoff and pollutant concentration.

The principal objectives of this research were to 1) demonstrate the applicability of a linear-systems approach for flood and water-quality analysis for Hawaiian watersheds and 2) develop techniques for deriving IUH and IPG.

Methodology

The modern unit-hydrograph method, the most popular analytical tool for flood hydrograph analysis, can be formulated based on linear systems theory. By this method direct runoff produced by a rain storm over a watershed system can be calculated by a convolution integration of effective rainfall and instantaneous unit hydrograph (IUH). Direct runoff or system input is the measured stream flow minus groundwater contribution or base flow. System output or effective rainfall is the rate of rainfall after subtracting the rate of infiltration and other “losses.” System impulse response function, or IUH for a linear watershed system, is the direct runoff produced by a watershed when it receives a unit-instantaneous-effective rainfall.

The linear systems approach has been successfully used in watershed hydrology to relate rainfall to runoff (Liu and Brutsaert 1978). This type of approach has also been used recently in river-water-quality analysis (Liu and Neill 2002) and in chemical transport in soils (Liu 1988). In this project the linear systems approach is also applied to watershed water-quality analysis to simulate waste loadings generated by a watershed receiving heavy storm.

Following the linear systems approach, storm runoff from a watershed at any time can be calculated by a simple convolution of the instantaneous unit hydrograph (IUH) and the effective rainfall. The IUH of a particular watershed is usually derived by performing an inverse operation based on one set of historical rainfall-runoff data. For watersheds that have no historical rainfall-runoff data, a method of synthetic IUH or "grey method" (Liu 1988) can be used. Using the grey method the linear systems model of a watershed rainfall-waste loading can be formulated as:

$$Y(t) = \int_0^t g(\tau)\, f(t-\tau)\, d\tau$$

Where *Y(t)* = the system output or contaminant concentration
g(t) = the system input or effective rainfall
f (t) = IPG in terms of a particular probability density functions.

Principal Findings and Significance

During the project period, the linear systems model of sediment transport as shown in the equation above was tested based on data collected in Mānoa Watershed during a rainstorm of March 14, 2009. In this case the system input is derived based on the available sediment over the watershed prior to the rainstorm and the effective rainfall; the system output is the total suspended solids (TSS) concentration at the watershed outlet.

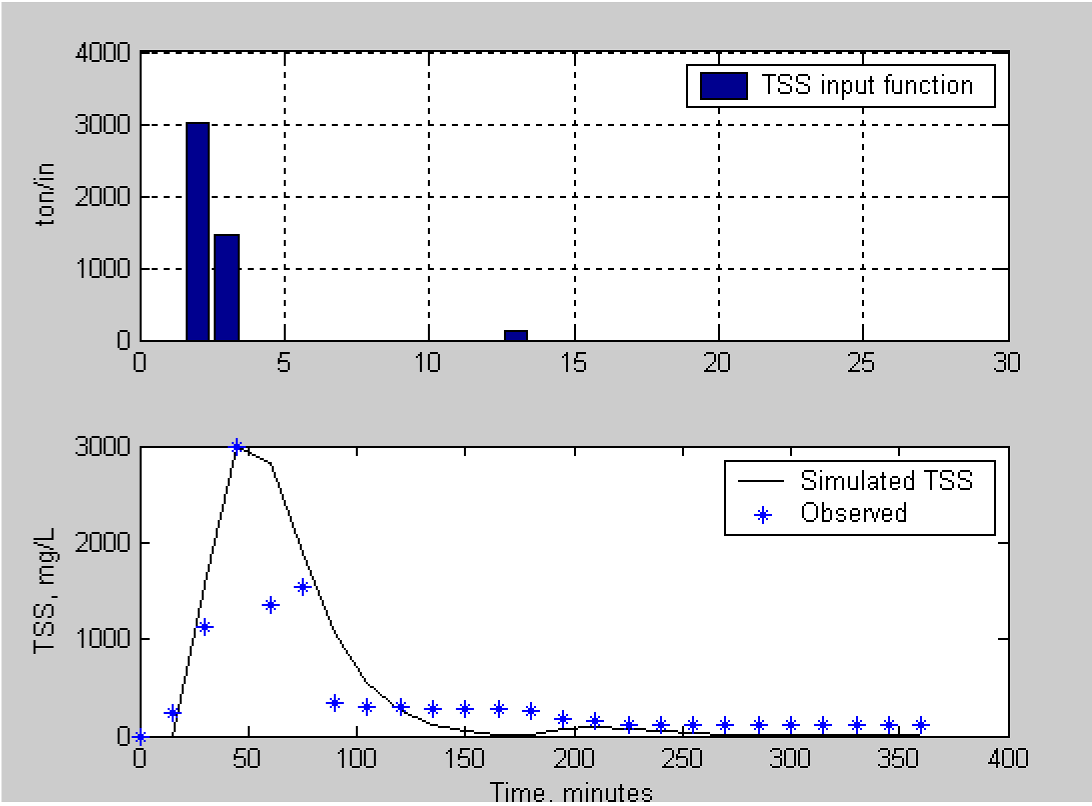

Figure 1. Simulated and Observed TSS loadings from Mānoa Watershed after a storm on March 14, 2009.

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Liu, C.C.K., and W.H. Brutsaert. 1978. A non-linear analysis of the relationship between rainfall and runoff for extreme floods. *Water Resources Research* 14 (1): 75–83.

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Sherman, L.K. 1932. Steam flow from rainfall by unit-graph method. *Engineering News Record* 108:501–505.

Identification and control of membrane bioreactor biofouling organisms using genetic fingerprinting

Basic Information

Title:	Identification and control of membrane bioreactor biofouling organisms using genetic fingerprinting
Project Number:	2006HI159B
Start Date:	3/1/2006
End Date:	8/31/2008
Funding Source:	104B
Congressional District:	Hawaii 1st
Research Category:	Engineering
Focus Category:	Water Supply, Treatment, Economics
Descriptors:	Membrane bioreactor, Biofouling, Genetic fingerprinting, Economics
Principal Investigators:	Roger Babcock

Publication

1. Babcock, R.W. Jr., and T. Huang. 2009. Controlling fouling in membrane bioreactors. Proceedings of the 2009 World Environmental & Water Resources Congress, Kansas City, Missouri.

Problem and Research Objectives

Membrane bioreactors (MBRs) are relatively new wastewater-treatment technologies promising exceptional treatment efficiency with a reduced surface-area footprint compared to conventional-treatment-process trains (Gander et al. 2000). A MBR uses an activated-sludge process in which the conventional secondary clarifiers are replaced by a membrane-separation process (either microfiltration or ultrafiltration).

Like other membrane systems—but to an even greater degree—MBRs are susceptible to biofouling (Chang et al. 2002). Biofouling is not a well-understood process but its effects increase operating pressures, reduce maximum flux (water passed through the membrane), increase recovery-cleaning requirements, and possibly reduce total membrane life (Cicek et al. 2001, LeClech et al. 2003). All of these effects of biofouling have adverse effects on either initial capital cost or ongoing operation-and-maintenance costs for MBRs. Because MBRs are quickly becoming the process of choice for water recycling there is a need to improve their cost efficiency by controlling the biofouling.

The primary research objectives were to 1) identify the microbial species present in MBRs under different operating conditions and 2) correlate the microbial species make-up in MBRs with biofouling conditions and water-quality parameters.

Methodology

This study included long-term operation of two different bench-scale MBRs. One MBR used a flat-sheet membrane technology provided by Enviroquip, Inc., utilizing Kubota membranes with 0.4 µm pore size. A second MBR used hollow-fiber technology provided by Ionics Corp. utilizing Mitsubishi membranes also with 0.4 µm pore size.

These bench-scale MBRs were operated using raw sewage pretreated only by passage through a 3mm-fine screen. Operating parameters that were varied include flux rate (flow per unit area of membrane, in this case 10 and 15 gallons per square foot of membrane per day [GFD]), solids retention time (SRT, in this case 5, 10, 20, and 40 days), organic/nutrient loading (raw sewage with/without supplemental organics), and state of oxygenation (high, low, or anoxic).

Steady-state operation was achieved under each set of conditions prior to proceeding to the next set of conditions. Operating and water-quality parameters that were monitored included trans-membrane pressure (TMP, continuous on-line measurement), soluble microbial products/extracellular polymeric substances (SMP/EPS) carbohydrate and protein fractions (cation exchange resin extraction, carbohydrates, and proteins), viscosity, particle size distribution (PSD), and soluble chemical oxygen demand (COD).

Microbial consortium samples from both mixed liquor and attached biofilms (cake layers) were collected from the bench-scale MBRs under various conditions. Samples of microbial populations in full-scale conventional activated-sludge systems and pilot-scale MBR systems were collected for comparisons. Genomic DNA for the total community was extracted en mass (using a culture-independent method which also yields unculturable organisms). Polymerase chain reaction (PCR) was used to produce 16S rRNA V3 region gene-amplification products.

Denaturing gradient gel electrophoresis (DGGE) was used to separate the 16S rRNA V3 region gene-amplification products to characterize the microbial community and monitor the dominant population.

The total number of DGGE bands provides an estimate of the microbial diversity within a given environment (a "genetic fingerprint"). The dominant microbial species were determined by DNA sequencing of genetic material taken from the DGGE bands. The sequenced DGGE bands were compared with the GeneBANK database to identify the bacteria responsible for biofouling.

Principal Findings and Significance

Total membrane flux resistance is easily calculated given the operating flux, viscosity, and TMP. Figures 1 and 2 show the total flux resistance during the various phases of the bench study for the Enviroquip, Inc., and Ionics Corp. MBRs, respectively. The slope of the total-resistance line can be considered the fouling rate.

For the Enviroquip, Inc., bench-scale MBR several observations can be made. First, at 10 GFD the fouling rate was essentially zero during the period of observation (meaning that the resistance held constant and fouling was minimal). Second, at 15 GFD there appear to be several different fouling rates. The fouling rate starts out low (about 2.8E10 $m^{-1}d^{-1}$), then apparently increases rapidly (to about 2.3E11 $m^{-1}d^{-1}$), slows down for a period (to about 2.9E10 $m^{-1}d^{-1}$), and then again rapidly increases (to about 2.3E11 $m^{-1}d^{-1}$). This phenomenon will require further investigation prior to reaching any possible conclusions. Third, when supplemental glucose was added to increase the feed strength by 50% for 7 days (with flux held at 15 GFD) the fouling rate did not appear to increase appreciably (to about 3.0E10 $m^{-1}d^{-1}$). Fourth, when the system was modified to eliminate the anoxic zone (with flux held at 15 GFD) the initial fouling rate seemed to decrease (to 6.4E09 $m^{-1}d^{-1}$). It was desired to correlate these phenomena with increases in the number of certain organisms—thereby implicating them indirectly as "fouling organisms." However this proved to be highly challenging and was not successful.

For the Ionics Corp. bench-scale MBR the fouling rate at 15 GFD (about 4.2E10 $m^{-1}d^{-1}$) was about three times as rapid as that at 10 GFD (about 1.4E10 $m^{-1}d^{-1}$). These fouling rates are all at SRT = 20 days.

During the relatively rapid increase in total resistance observed for the Enviroquip, Inc., bench-scale MBR at 15 GFD, the protein EPS and SMP in the mixed liquor were fairly steady but the permeate SMP showed an interesting trend (Figure 3). Figure 3 shows that the permeate SMP was fairly steady until a certain point (30–35 days into the 49-day run) when the value dropped off suddenly (meaning all SMP was retained). This is apparently an indication of severe fouling which could possibly be associated with specific bacteria species; however no such correlations were achieved. No trends in the protein fraction of EPS or mixed-liquor SMP that could be useful for predicting fouling were apparent in this data set.

Figures 4, 5, and 6 show the type of data obtained in the biofouling-genetics study. Each vertical lane represents a different sample of community DNA, each horizontal band represents a different bacteria, and brighter bands indicate larger numbers of biomass (dominant species).

In Figure 4 it can be observed that there are differences in the dominant species of bacteria in the Huber MBR as compared to the Ionics Corp. MBR and that speciation changes over time in the MBRs.

Figure 5 shows the bench-scale Enviroquip, Inc., MBR under non-fouling conditions when the SRT was 20 days, the flux was 10 GFD, and no anoxic zone was included. In this case it can be observed that one dominant bacterium seems to wash out (upper band) and other bacteria either fluctuate, appear, or disappear. The biofilm sample (lane #6) taken at the end of this phase of experiments may be the most interesting since we can see that the dominant bacteria species are almost completely different from those in the mixed liquor, that there are fewer species present, and that three bacteria are highly concentrated (dominant).

Figure 6 shows the bench-scale Enviroquip, Inc., MBR under high-fouling conditions when the SRT was 20 days and the flux was 15 GFD. In this case there appears to be about three types of bacteria that are more dominant at the end when fouling was severe that were either less prevalent or were not present at the beginning. These bacteria, therefore, may be associated with fouling.

These bands were cut out for sequencing to identify the bacteria species. The data obtained from the sequencing was queried with GeneBANK to identify the bacteria. The results are shown in Figures 7 and 8.

Future work is necessary to further study these and other identified fouling bacteria species by reviewing their physiological/morphological characteristics to see if they can be biologically or chemically controlled to reduce their biofouling potential.

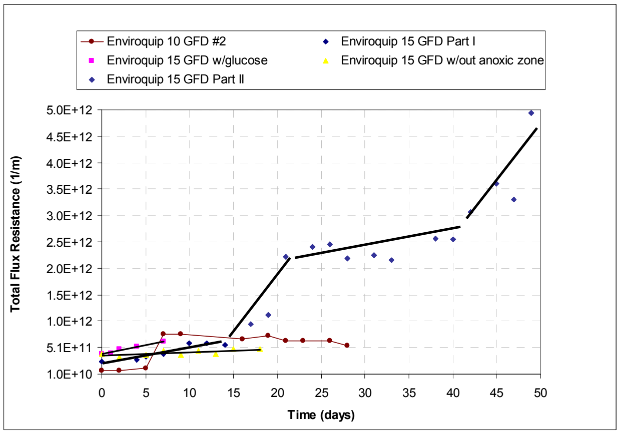

Figure 1. Fouling rates during operation of bench-scale Enviroquip, Inc., MBR

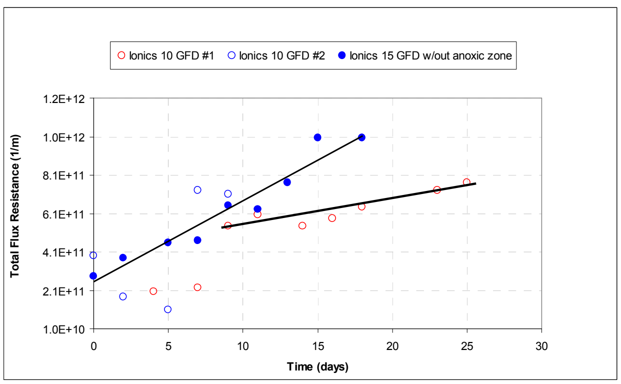

Figure 2. Fouling rates during operation of bench-scale Ionics Corp. MBR

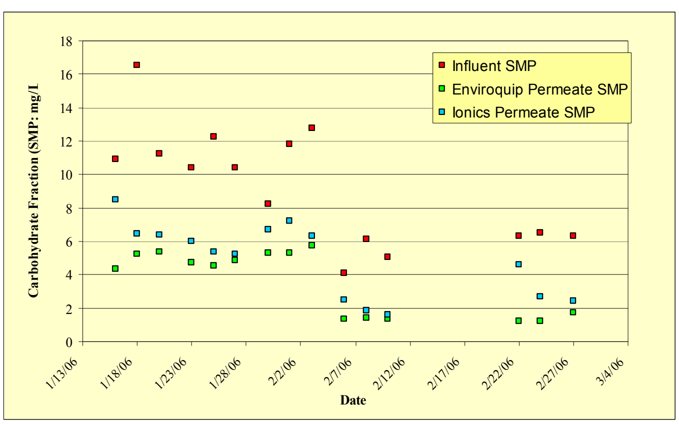

Figure 3. Comparison of permeate carbohydrate SMP from bench-scale MBRs

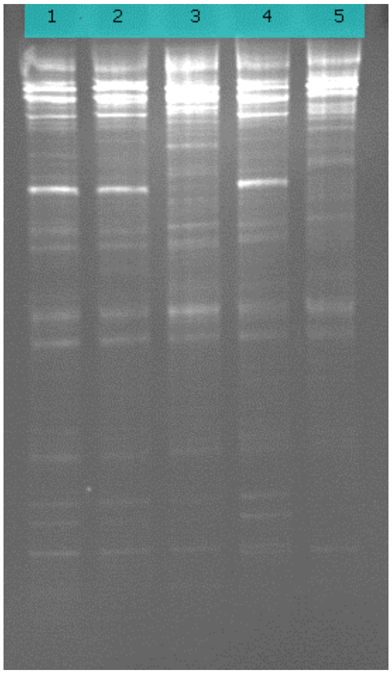

Figure 4. DGGE analyses of pilot MBR mixed-liquor samples. Lane 1: Huber 6/29/07, lane 2: Huber 7/6/07, lane 3: Ionics 6/29/07, lane 4: Huber 7/20/07, lane 5: Ionics 7/20/07

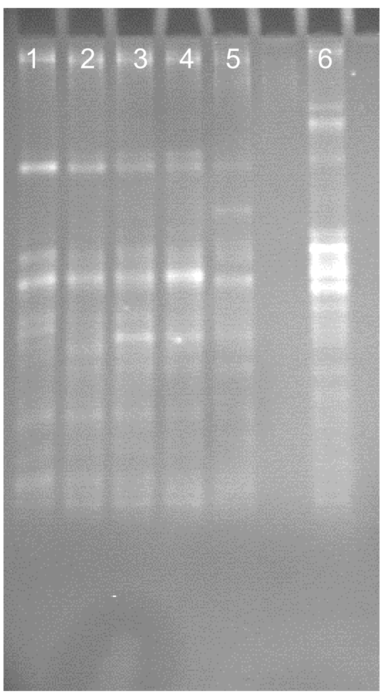

Figure 5. DGGE analyses of bench-scale Enviroquip, Inc., MBR mixed-liquor samples under non-fouling conditions. Lane 1: 5/24/07, lane 2: 5/31/07, lane 3: 6/7/07, lane 4: 6/14/07, lane 5: 6/21/07, lane 6: biofilm 6/28/07

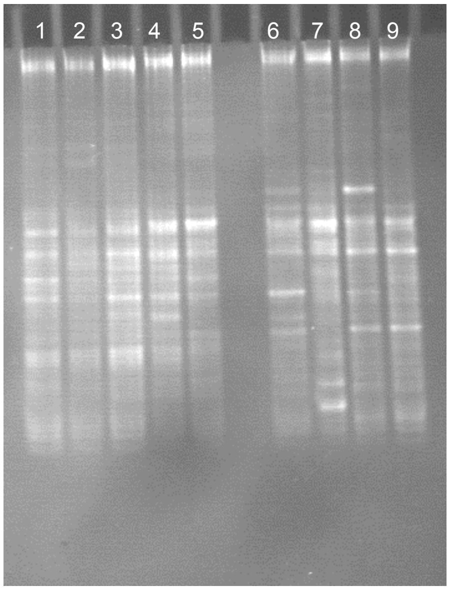

Figure 6. DGGE analyses of bench-scale Enviroquip, Inc., MBR mixed-liquor samples under high-fouling conditions. Lane 1: 3/8/07, lane 2: 3/15/07, lane 3: 3/22/07, lane 4: 3/29/07, lane 5: 4/5/07, lane 6: 4/19/07, lane 7: 4/26/07, lane 8: 5/3/07, lane 9: 5/10/07

```
> gb|AY302125.1|  Uncultured bacterium clone DSBR-B050 16S ribosomal RNA
gene,
partial sequence
Length=1450

 Score =  323 bits (163),  Expect = 1e-85
 Identities = 163/163 (100%), Gaps = 0/163 (0%)
 Strand=Plus/Plus

Query  6     TTGGTCAATGGAGGGAACTCTGAACCAGCCATGCCGCGTGAAGGATGACGGCCCTCTGGG  65
DEFINITION  Uncultured bacterium clone DSBR-B050 16S ribosomal RNA gene,
            partial sequence.ACTCTGAACCAGCCATGCCGCGTGAAGGATGACGGCCCTCTGGG  396
ACCESSION   AY302125
VERSION     AY302125.1  GI:34538342GCGAAAAAACGGGATTTATCCTGGACTGACGGTACCAT  125
KEYWORDS    ENV. ||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
SOURCE      uncultured bacterium GGGGCGAAAAAACGGGATTTATCCTGGACTGACGGTACCAT  456
  ORGANISM  uncultured bacterium
            Bacteria; environmental samples.AGCCGCGGTAAT  168
REFERENCE   1  (bases 1 to 1450) ||||||||||||||||||||||||
  AUTHORS   Ginige,M.P., Keller,J. and Blackall,L.L.TAAT  499
  TITLE     The analysis of a methanol denitrifying microbial community by
            stable isotope probing, full cycle rRNA analysis and fluorescence
            in situ hybridization-microautoradiography
  JOURNAL   Unpublished
REFERENCE   2  (bases 1 to 1450)
  AUTHORS   Ginige,M.P., Keller,J. and Blackall,L.L.
  TITLE     Direct Submission
  JOURNAL   Submitted (18-MAY-2003) Advanced Wastewater Management Centre,
            The University of Queensland, Ritchie Building (64A), Research
            Road, St Lucia, Brisbane, QLD 4072, Australia
```

Figure 7. Denitrifying biofouling organism identified

```
> dbj|AB205887.1|  Uncultured bacterium gene for 16S rRNA, partial sequence
clone:12C-M49
Length=578

 Score =  323 bits (163),  Expect = 1e-85
 Identities = 163/163 (100%), Gaps = 0/163 (0%)
 Strand=Plus/Plus

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             ||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
DEFINITION   Uncultured bacterium gene for 16S rRNA, partial sequence,GGG  86
             clone:12C-M49.
ACCESSION    AB205887 TGGATGGGGCGAAAAAACGGGATTTATCCTGGACTGACGGTACCAT  125
VERSION      AB205887.1  GI:73912549|||||||||||||||||||||||||||||||||||||
KEYWORDS     ENV.GGGGCGAAAAAACGGGATTTATCCTGGACTGACGGTACCAT  146
SOURCE       uncultured bacterium
  ORGANISM   uncultured bacteriumTCCGTGCCAGCAGCCGCGGTAAT  168
             Bacteria; environmental samples.||||||||||||
REFERENCE    1 AGCCGCGGTAAT  189
  AUTHORS    Osaka,T., Yoshie,S., Tsuneda,S., Hirata,A., Iwami,N. and
             Inamori,Y.
  TITLE      Identification of Acetate- or Methanol-Assimilating Bacteria
             under Nitrate-Reducing Conditions by Stable-Isotope Probing
  JOURNAL    Microb. Ecol. 52 (2), 253-266 (2006)
   PUBMED    16897304
REFERENCE    2  (bases 1 to 578)
  AUTHORS    Osaka,T., Yoshie,S., Tsuneda,S., Hirata,A. and Inamori,Y.
  TITLE      Direct Submission
  JOURNAL    Submitted (01-MAR-2005) Toshifumi Osaka, Waseda University,
             Department of Chemical Engineering; 3-4-1 Ohkubo, Shinjyuku-ku,
             Tokyo 169-8555, Japan (E-mail:toshifumi-oggy@suou.waseda.jp,
             Tel:81-3-5286-3210, Fax:81-3-3209-3680)
```

Figure 8. Nitrate-reducing biofouling organism identified

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Chang, I.S., P. LeClech, B. Jefferson, and S. Judd. 2002. Membrane fouling in membrane bioreactors for wastewater treatment. *J. Environ. Eng.* 128:1018.

Cicek, N., J. Macomber, J. Davel, M.T. Suidan, J. Audic, and P. Genestet. 2001. Effect of solids retention time on the performance and biological characteristics of a membrane bioreactor. *Water Sci. Technol.* 43:43.

Gander, M., B. Jefferson, and S. Judd. 2000. Aerobic MBRs for domestic wastewater treatment: a review with cost considerations. *Sep. Purif. Technol.* 18:119.

LeClech, P., B. Jefferson, and S.J. Judd. 2003. Impact of aeration, solids concentration and membrane characteristics on the hydraulic performance of a membrane bioreactor. *J. Membr. Sci.* 218:117.

Efficient Water Management and Block Pricing for Integrated Aquifers: Lessons from Southern Oahu

Basic Information

Title:	Efficient Water Management and Block Pricing for Integrated Aquifers: Lessons from Southern Oahu
Project Number:	2007HI183B
Start Date:	3/1/2007
End Date:	8/31/2008
Funding Source:	104B
Congressional District:	Hawaii 1st
Research Category:	Social Sciences
Focus Category:	Economics, Management and Planning, Groundwater
Descriptors:	Groundwater management, Dynamic optimization, Multiple renewable resources
Principal Investigators:	James A. Roumasset

Publication

1. Kaiser, B., B. Pitafi, J. Roumasset, and K. Burnett. 2007. “The economic value of watershed conservation,” in A. Fares and A. El-Kadi (eds.), Land Management Impacts on Coastal Watershed Hydrology. Southampton, UK: WIT Press.

Problem and Research Objectives

Most previous studies on the topic of groundwater management have limited their attention to the case of a single aquifer. However one can identify situations where multiple sources of groundwater are accessible to a single city or a dense cluster of cities. For example, the Honolulu Board of Water Supply (HBWS) on the island of O‘ahu, Hawai‘i, currently extracts water from both the Honolulu and Pearl Harbor aquifers and pumps this water into an interconnected pipeline that serves both consumption districts. Water is being imported from Pearl Harbor to meet the large and growing demand in Honolulu.

Thus the problem requires an integrated analytical model that determines optimal groundwater use when water can be extracted from two sources.

Methodology

Following the theoretical framework laid out by Pitafi and Roumasset (forthcoming) we applied an optimal control model to the Honolulu and Pearl Harbor aquifers independently and identified the efficient paths of water extraction for each. The purpose of this exercise was both to update previous estimates for Honolulu (Pitafi and Roumasset, forthcoming) and Pearl Harbor (Krulce, Roumasset, and Wilson 1997) and to provide a benchmark for comparison with the joint-management scenario.

Our methodology differed from previous studies in several ways. Most notably we attempted to incorporate spatial aspects into our extraction cost functions by considering well placements and depths. Low ground-surface elevation wells near the coast tend to have lower extraction costs but they are also first to face the effects of saltwater intrusion.

As the aquifer is drawn down the saltwater interface rises to the well bottoms—at which point a decision must be made. The managing authority may 1) abandon low-elevation wells and increase extraction at high-cost higher-elevation wells; 2) impose a constraint on extraction so that the hydraulic head does not fall further in order to protect the lower-elevation wells; or 3) abandon the coastal wells and drill new and expensive higher-elevation wells. In our simulations we examined the first two possibilities and found that the results differed significantly.

The multiple-aquifer model is an extension of the optimal control model for the single-aquifer case. The objective is to choose time paths for groundwater extraction and desalinated-water production to maximize the present value of the net social surplus from water use (consumer surplus less producer costs):

$$\underset{q_t^i, q_t^2, b_t}{Max}\, PV\ ,\ PV = \int_0^{\infty} e^{-rt} \left(\int_0^{q_t^1+q_t^2+b_t} D^{-1}(x,t)dx - q_t^1 \cdot c_1(h_t^1) - q_t^2 \cdot c_2(h_t^2) - b_t \cdot c_b \right) dt$$

$$\begin{aligned} \text{subject to} \quad & \dot{h}_t^1 = n_1(h_t^1) - q_t^1 \\ & \dot{h}_t^2 = n_2(h_t^2) - q_t^2 \\ & q_t^1 \geq 0,\ q_t^2 \geq 0,\ b_t \geq 0 \\ & h_t^1 \geq h_{\min}^1,\ h_t^2 \geq h_{\min}^2,\ h_0^1 \text{ and } h_0^2 \text{ given} \end{aligned}$$

Manipulation of the Pontryagin conditions for this dynamic optimization problem gives an expression for the efficiency price:

$$p_t^i = c_i(h_t^i) + \frac{\dot{p}_t^i - c_i'(h_t^i) \cdot n_i(h_t^i)}{r - n_i'(h_t^i)} \qquad \text{for } i = 1,2$$

This is the usual expression for the efficiency price of a renewable resource; price is equal to the extraction cost plus a marginal user cost. However only one price is effective at any given point in time so we also have the condition that:

$$\begin{aligned} & p_t \leq c_1(h_t^1) + \lambda_t^1, && \text{if } <, \text{ then } q_t^1 = 0 \\ & p_t \leq c_2(h_t^2) + \lambda_t^2, && \text{if } <, \text{ then } q_t^2 = 0 \\ & p_t \leq c_b, && \text{if } <, \text{ then } b_t = 0 \end{aligned}$$

In other words, water is extracted from the resource with the lowest extraction cost plus in situ shadow value. When the efficiency prices are equal, water is extracted from both aquifers simultaneously.

We used pumping and cost data provided by HBWS to estimate the parameters required for numerical simulations of our model. A computer algorithm written in *Mathematica* was then used to estimate the optimal time paths of the efficiency price and hydraulic-head levels.

Principle Findings and Significance

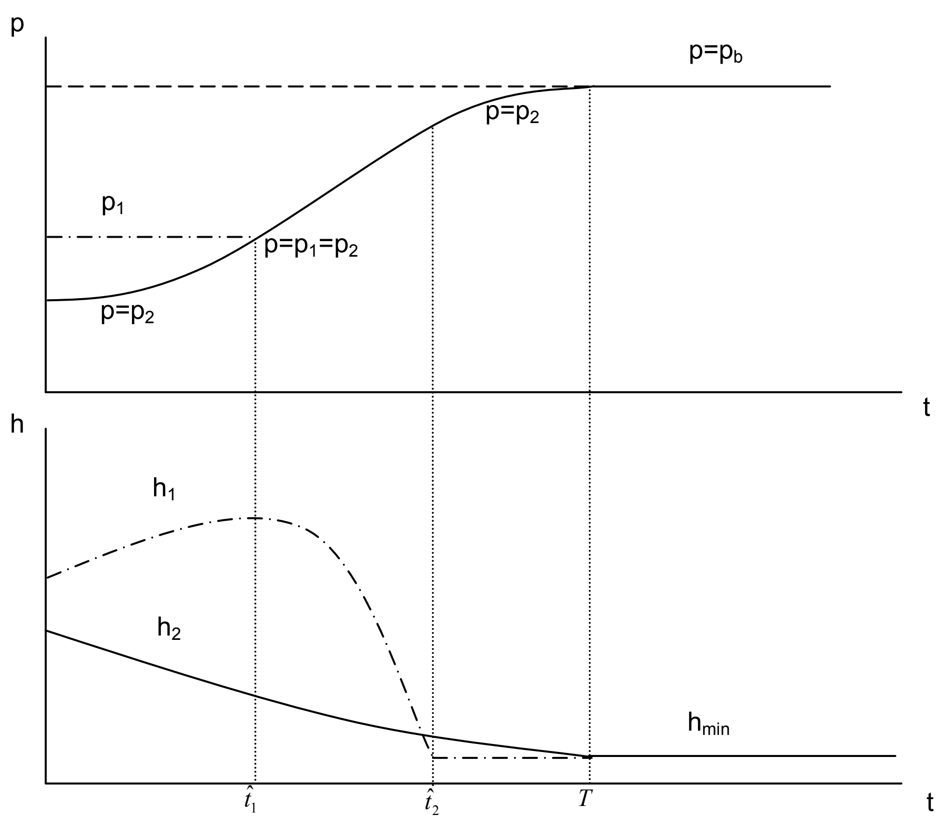
For comparative purposes we ran numerical simulations for the independent management of Honolulu and Pearl Harbor aquifers. The results indicate that in both cases, switching from status quo to efficiency pricing can extend the useful life of the aquifer for up to twenty years. Economic efficiency requires switching to desalination after 148 and 167 years for Honolulu and Pearl Harbor respectively, much later than was calculated in previous studies. This is largely due to the fact that the previous Honolulu study did not consider that a large percentage of the water consumed in Honolulu is actually being imported from

Pearl Harbor and that total draft for Pearl Harbor has declined over the past twenty years. The welfare gain from switching pricing structures is on the order of tens of millions of dollars for Honolulu and hundreds of millions of dollars for Pearl Harbor, or 1–2% of the status quo welfare.

When a constraint is placed on the hydraulic-head level to ensure that coastal wells remain usable for freshwater extraction, the results change drastically. For the case of Honolulu, a hydraulic-head constraint of 22.4 feet was imposed in order to protect the deepest wells. The resulting optimal efficiency price path rises drastically and the switch to desalination occurs after about twenty-five years, less than 1/6th of the time it takes for the "abandon as you go" strategy.

Aside from spatial issues on the demand side, our joint-aquifer analysis indicates that Pearl Harbor should be used exclusively for a period of time, after which both aquifers are used simultaneously. Eventually the Honolulu aquifer is depleted and the Pearl Harbor aquifer is again used exclusively until it, too, is exhausted.

At that point extraction from both aquifers is limited to natural recharge and the remainder is supplied by desalination. The stages of extraction are illustrated in the figure below.



Preliminary analysis suggests that welfare gains associated with switching from the status quo pricing structure to integrated management are larger in both absolute and percentage terms than the gains from switching to efficient but independent management of the Honolulu and Pearl Harbor districts.

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Pitafi, B., and J.A. Roumasset. Forthcoming. Pareto-improving water management over space and time: The Honolulu case. *American Journal of Agricultural Economics*.

USGS Grant No. 07HQAG0162 Assessing Effects of Intraborehole Flow in Deep Monitoring Wells on Estimates of Aquifer Salinity Profiles

Basic Information

Title:	USGS Grant No. 07HQAG0162 Assessing Effects of Intraborehole Flow in Deep Monitoring Wells on Estimates of Aquifer Salinity Profiles
Project Number:	2007HI241S
Start Date:	9/1/2007
End Date:	12/31/2008
Funding Source:	Supplemental
Congressional District:	Hawaii 1st
Research Category:	Ground-water Flow and Transport
Focus Category:	Groundwater, Water Quality, Water Supply
Descriptors:	Borrehole flow, Deep-monitor wells, Salinity profiles
Principal Investigators:	Aly I El-Kadi

Publication

1. Rotzoll, K., C.D. Hunt Jr., and A.I. El-Kadi. 2008. The effect of borehole flow on salinity profiles from deep monitor wells in Hawaii: Eos Trans. AGU, 89 (52) Fall Meeting Supplement, Abstract H21D-0849.
2. Rotzoll, K., C.D. Hunt, Jr., and A.I. El-Kadi. 2009. The effect of borehole flow on salinity profiles in Hawaii. 35th annual Hawaii section American Water Works Association Conference. Honolulu, 13–15 May 2009
3. Rotzoll, K. (in review). Causes and effects of borehole flow on deep monitor wells in Hawaii. U.S. Geological Survey Scientific Investigations Report.

Problem and Research Objectives

Regulation of groundwater withdrawals at some aquifer locations in Hawaiʻi is based principally on salinity-versus-depth profiles from adjacent deep-monitoring wells. Salinity profiles are being used to monitor the midpoint of the transition zone between freshwater and saltwater as a proxy to track the thickness of the overlying freshwater lens (Meyer and Presley 2001; Gingerich and Voss 2005).

This information is being used by the Hawaiʻi Commission on Water Resource Management for sustainable-yield estimates utilizing the RAM2 model (Mink 1980; Mink 1981; Liu 2006; Liu 2008). Salinity profiles are being used, as well, for calibrating regional density-dependent groundwater-flow models (Souza and Voss 1987; Oki, Souza et al. 1996). These models provide insights into groundwater availability under different recharge-and-withdrawal scenarios (Oki 2005; Gingerich 2009).

Borehole geophysical logging in Hawaiʻi has shown some evidence of subtle vertical borehole flow in some cases (Paillet and Hess 1995; Paillet, Williams et al. 2002). Because of possible borehole-flow effects, salinity profiles from deep-monitor wells may not accurately reflect the salinity distribution in the surrounding aquifer with changing depth.

The definitive questions then become: "Is this subtle borehole flow sufficient to invalidate the depth-salinity profiles that are being observed?" Or: "Is the borehole flow great enough that the observed salinity profile in the borehole is substantially different from that in the adjacent aquifer?"

A final question concerns the use of and management intent for these deep-monitoring wells: "Are salinity profiles from deep-monitoring wells sufficiently invalid that they cannot be used to monitor long-term changes in the adjacent aquifers over time periods ranging from years to decades?"

"Years-to-decades" is currently the anticipated timescale in response to pumping for saltwater intrusion into the aquifers in Hawaiʻi (Visher and Mink 1964). Thus far this topic has not been comprehensively addressed in published literature.

The objective of this research is to evaluate the potential for vertical borehole flow in deep-monitor wells that may result in inaccurate or misleading information being used for groundwater management in Hawaiʻi.

Methodology

Two approaches will be used: 1) evaluating and summarizing existing work to date, and 2) consulting with experts in borehole geophysical logging to design a strategy for further fieldwork.

Case Studies —Field data and studies in Hawaiʻi on borehole flow by Paillet and Hess (1995) and Paillet et al. (2002) will be reviewed. Existing geophysical logs and salinity profiles will be inspected for evidence of vertical flow and profile disturbance. Some deep-monitor wells are currently suspected of having such significant borehole flow that salinity profiles from these wells are probably invalid measurements of the salinity distribution in the adjacent aquifers.

One indicator of possible vertical borehole flow sometimes evident in salinity profiles is a step-like change in electrical-conductivity data. These "kinks" are evident where significant quantities of water may be either entering or exiting the uncased part of the borehole. Salinity profiles frequently show multiple step-like changes in electrical conductivity. This makes it difficult to accurately determine the principal direction of borehole flow and whether or not the measured conductivity accurately estimates the salinity in the adjacent aquifer (Oki and Presley 2008).

On the island of Oʻahu, Hawaiʻi, there is a classic case where a fully-open deep-monitor well has been sited too close to large-capacity water-supply wells. At this site the drawdown from the pumping wells appears to draw brackish water up the bore of the monitor well. For wells away from obvious pumping disturbances much less evidence for salinity-profile disturbance exists.

In a second example vertical borehole flow is likely to occur in a deep-monitoring well which taps a degraded irrigation-return groundwater layer. A well fitting this description is located at the discharge end of the central Oʻahu flow system where upward vertical-head gradients are expected. A deep-monitor well in this area has lower nitrate than surrounding shallower observation wells and this may indicate upward flow of "fresher" water from intermediate depths. Considerable chemical and tracer data are available for the deep-monitor well which, if carefully evaluated, may provide insights into quantifying the amount of vertical borehole flow. The possible presence of seasonal effects currently "hidden" in the data in existing salinity logs will be examined by differentiating log data from various dates to see if differences follow the expected trend.

Strategy for Further Fieldwork—Results of the case studies above will be used to design a strategy for fieldwork on Oʻahu, Hawaiʻi.

Separately, it is likely that new data logging will be proposed for the Waiehu deep-monitor well in the ʻIao Valley area of the island of Maui, Hawaiʻi. This well is particularly important to the management of ongoing pumping activities at this location as, under the sustainable-yield concept, the midpoint of the transition zone in the salinity profile of this deep-monitor shows a steady rise over the last three decades.

Geophysical specialists in borehole logging will be asked to propose methods not to simply demonstrate that there is borehole flow but to definitively answer the critical question: Can it be demonstrated that, in certain cases, the borehole-salinity reference profile differs substantially from the adjacent aquifer-salinity profile?

Proposed strategies may include induction tools that "look outside" the borehole and into the formation (Keys 1990). The use of such tools would require adequate measurements of formation porosity and of the bulk resistivity of the solid-basalt matrix and the application of Archie's Law. It would be essential that the geophysical logging methodology be able to differentiate between resistivity measured for the fluid and that measured for the surrounding formation.

Other deep-monitor wells on various Hawaiian islands may also be proposed for additional work. Approaches may include salinity profiling under ambient and pumped conditions or repeat profiling at seasonal intervals (to take advantage of naturally-imposed vertical-head gradients).

One example of a naturally-imposed vertical-head gradient is the seven-foot rise in the regional water table on Oʻahu that has accompanied a recent recharge event after five dry years. Repeat sampling data may be accessed through ongoing logging programs of the Hawaiʻi Commission on Water Resource Management and county water department records.

Challenges—Local stakeholders believe that salinity profiles from open boreholes are a reasonable indicator of adjacent aquifer salinity. Well owners may not be enthusiastic in their support of uncompensated geophysical research in their wells considering unexpected high costs associated with rehabilitating any wells damaged by logging tools.

Finally, valuable information can be obtained through a network of short-screened or point-piezometer measurements to define vertical-head gradients or the true-salinity distribution in the adjacent aquifer. High costs, however, would limit such efforts—especially for wells exceeding a depth of one thousand feet.

Preliminary Findings and Significance

Step-like changes in conductivity are evident in almost all available salinity profiles. A regional trend, supported by basin-wide groundwater-flow dynamics, is prominent as major downward flow components that occur in recharge areas and major upward flow components that are seen in discharge areas towards the coast. Several salinity profiles in deep-monitor wells indicate large kinks as signs of vertical borehole flow. The largest deviation from theoretical aquifer salinity occurs in deep-monitor wells located in area extending from east Pearl Harbor to Kalihi on Oʻahu. However no significant correlation exists between proximity to pumping centers and the magnitude of kinks in the profiles.

Is the vertical borehole flow so great that salinity-profile data are invalid measurements of adjacent aquifer salinity? We can not answer this yet for all deep-monitor wells but, in tracking for the midpoint of the transition zone between freshwater and saltwater, the Beretania deep-monitor well case study shows depth displacements caused either by barometric pressure and tidal fluctuations or by nearby withdrawal from pumping centers to be inconsequential.

The 1 mS/cm concentration is indicative for the top of the transition zone between freshwater and saltwater. Contrary to the midpoint, several salinity profiles indicate 100 to 400 ft depth displacements of the 1 mS/cm concentration in deep-monitor wells near pumping centers.

In many cases studied in this project, poor quality control of salinity profiles is hindering data interpretation. It can be concluded, however, that this continuing research is an important step towards assessing the significance of the problem.

Should the results from this project indicate significant unreliability of the salinity-profile data from deep-monitoring wells in determining adjacent aquifer salinity, local stakeholders are likely to become more interested in funding further fieldwork.

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Oki, D.S., W.R. Souza, E.L. Bolke, and G.R. Bauer. 1996. *Numerical analysis of ground-water flow and salinity in the Ewa area, Oahu, Hawaii*. Open-File Report 96-442. Honolulu: U.S. Geological Survey.

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. Open-File Report 95-383. Honolulu: U.S. Geological Survey.

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, no. 6:577–585.

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, no. 1:17–41.

Visher, F.N., and J.F. Mink. 1964. *Ground-water resources in southern Oahu, Hawaii*. Water-Supply Paper 1778. Honolulu: U.S. Geological Survey.

Improving Water Resource Assessment in Hawaii by Using LiDAR Measurements of Canopy Structure to Estimate Rainfall Interception

Basic Information

Title:	Improving Water Resource Assessment in Hawaii by Using LiDAR Measurements of Canopy Structure to Estimate Rainfall Interception
Project Number:	2008HI224B
Start Date:	3/1/2008
End Date:	2/28/2009
Funding Source:	104B
Congressional District:	Hawaii 1st
Research Category:	Climate and Hydrologic Processes
Focus Category:	Hydrology, Ecology, Water Quantity
Descriptors:	Throughfall, Stemflow, Wet-canopy evaporation
Principal Investigators:	Thomas Giambelluca, Qi Chen

Publication

Problem and Research Objectives

Water resources in Hawaiʻi continue to experience increasing demand, putting pressure on existing sources and increasing the need for better estimates of resource capacity (Oki 2002). For groundwater sources, in particular, reliable estimates of sustainable yield limits are critically important. Groundwater recharge estimates, in turn, are needed to determine accurate safe yield limits. Recharge is highly spatially variable in Hawaiʻi (Giambelluca 1983) because of extreme gradients in precipitation and evapotranspiration (ET). The accuracy of recharge estimates in Hawaiʻi has been limited by a lack of direct measurements of ET within forested recharge areas.

Recent research has improved our knowledge of stand-level ET in Hawaiʻi and pointed to the need to better understand interception loss—the amount of rainfall intercepted by leaves and stems and subsequently evaporated (Giambelluca et al. 2009). The amount of interception loss, which can vary from 10% to 50% of incoming precipitation (Roth et al. 2007), is strongly influenced by canopy structure (especially canopy gap fraction); leaf, stem and epiphyte storage capacity; and branch angle (Rutter et al. 1975; Gash 1995), and, hence, is highly variable across the forested landscape.

Alien trees, some of which—such as *Psidium cattleianum* (strawberry guava)—are highly invasive, are markedly different in structure from native trees such as *Metrosideros polymorpha (ʻōhiʻa).* Very little is known about the rate and spatial variability of interception loss and the effects of alien tree introductions on interception in Hawaiʻi. Better estimates of interception are needed to improve water-resource assessments. Such improvements would be highly valuable to water-supply purveyors of the various counties and state water planners. The traditional method for measuring interception, based on canopy water balance, is difficult and very limited in spatial coverage. However recent advances in ground-based and airborne Light Detection and Ranging (LiDAR) technology offer the promise of spatially-distributed estimates of interception using a physically-based approach (Roth et al. 2007).

Methodology

We used a ground-based LiDAR system to map the three-dimensional above-ground biomass distribution at two study sites within Hawaiʻi Volcanoes National Park. The two sites represent an intact native *M. polymorpha* forest and a *P. cattleianum*-dominated invaded forest.

At each site we were already operating a flux tower fully equipped with eddy-covariance, micrometeorological, and canopy-water-balance sensor systems. Using LiDAR we acquired high-resolution scans of each stand (Figure 1) over an area of 0.36 ha surrounding each tower.

In an adaptation of the Gash (1995) revised analytical interception model, these data are used to determine the following canopy structural parameter values: canopy capacity, canopy cover fraction, trunk storage capacity, free throughfall coefficient, and fraction of water diverted to stemflow. We are using the model to estimate throughfall (TF), stemflow (SF), and interception (I), and compare the results against our measurements of TF and SF at each site.

Principal Findings and Significance

This work is still in progress. To date we have completed the LiDAR scans at the two field sites in Hawai‘i Volcanoes National Park (Figure 1). These data are currently being analyzed

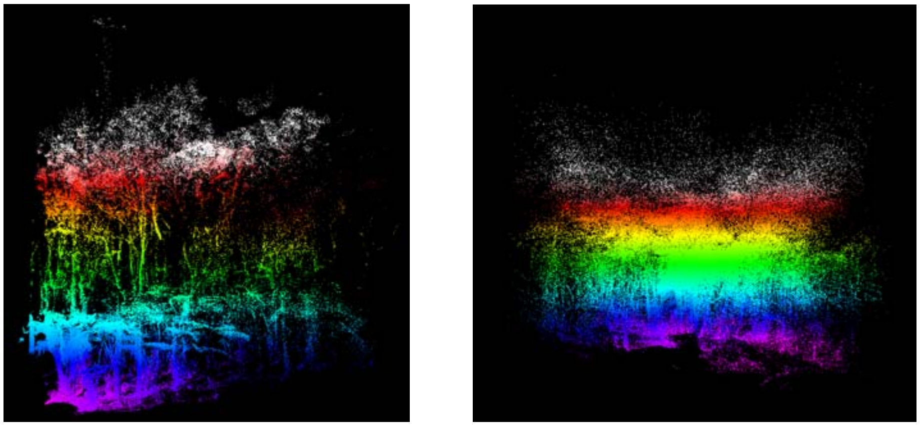

Figure 1. Image derived from high-resolution LiDAR scans done at Thurston Lava Tube (left) and Ōla‘a (right).

and new methods are being developed to extract information relevant to setting parameter values in a canopy rainfall interception model. Based on preliminary analysis, vertical biomass profiles have been derived for the two sites (Figure 2).

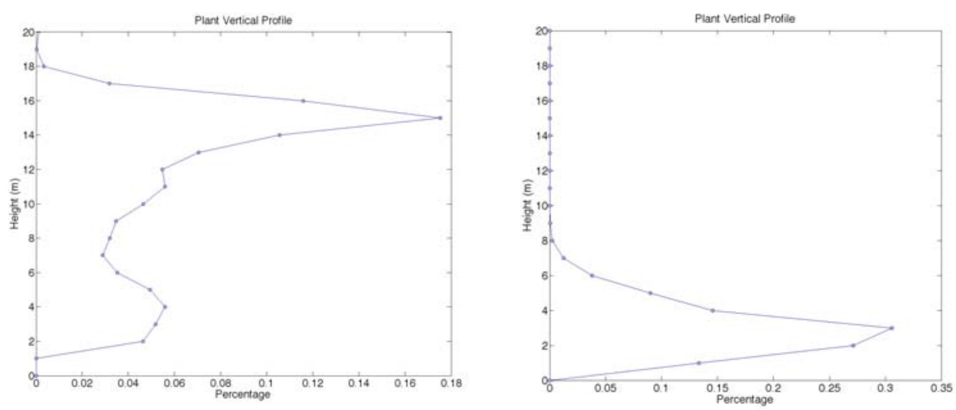

Figure 2. Vertical biomass profiles derived from high-resolution LiDAR scans done at Thurston Lava Tube (left) and Ōla‘a (right).

We are also developing and testing a new interception model to take advantage of the vertical detail in canopy-structure information we expect to be able to obtain from the LiDAR data. The new model divides the vegetation into three layers to represent the crown, subcrown, and fern layers of the canopy. In addition, epiphytes will be represented separately in each layer.

The model differs from other interception models by explicitly accounting for water storage and movement at different levels in the canopy. Utilizing LiDAR-derived information on the vertical distribution of leaf, branch, and stem mass, vertical variations in both water storage and evaporative demand are represented in the model. This allows for more realistic simulation of the wetting, drainage, and drying process. Figure 3 shows a preliminary model simulation of throughfall and stemflow at the Ōla‘a site for a storm in June 2007.

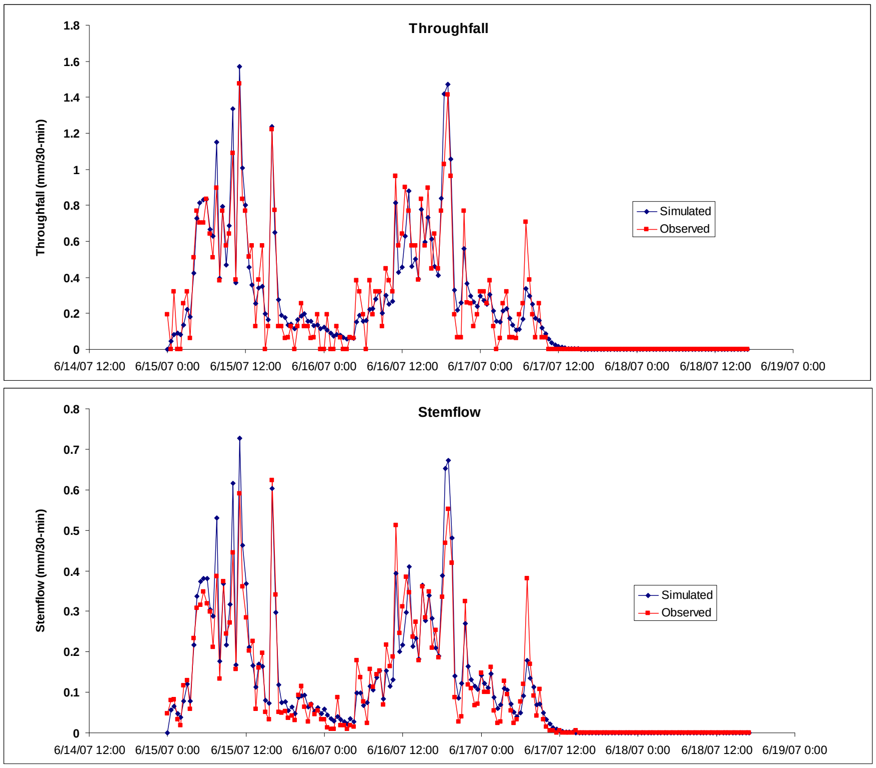

Figure 3. Simulated and observed throughfall (top panel) and stemflow (bottom panel) for a sample period in June 2007 at the Ōla‘a study site.

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Integrated Management of Multiple Aquifers in the Face of Climate Change

Basic Information

Title:	Integrated Management of Multiple Aquifers in the Face of Climate Change
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Research Category:	Social Sciences
Focus Category:	Economics, Management and Planning, Groundwater
Descriptors:	Groundwater management, dynamic optimization, multiple renewable resources
Principal Investigators:	James A. Roumasset

Publication

1. Pitafi, B.A. and J.A. Roumasset. 2009. "Pareto-improving water management over space and time: The Honolulu case," American Journal of Agricultural Economics, 91:138–153.
2. Pongkijvorasin, S., J. Roumasset, and T.K. Duarte. 2007. "Coastal Groundwater Management with Nearshore Resource Interactions." University of Hawai‘i at Mānoa Department of Economics Working Paper #07-13. Accessible online: http://www.economics.hawaii.edu/research/workingpapers/WP_07-13.pdf.
3. Pongkijvorasin, S., J. Roumasset, T.K. Duarte, and K. Burnett. 2008. "Renewable Resource Management with Stock Externalities: Coastal Aquifers and Submarine Groundwater Discharge." University of Hawai‘i at Mānoa Department of Economics Working Paper #08-08R. Accessible online: http://www.economics.hawaii.edu/research/workingpapers/WP_08-8R.pdf.
4. Roumasset, J.A., and C.A. Wada. 2009. "Integrated Management of the South O‘ahu Aquifer System: A Spatial and Temporal Approach." University of Hawai‘i at Mānoa Department of Economics Working Paper #09-2. Accessible online: http://www.economics.hawaii.edu/research/workingpapers/WP_09-2.pdf.
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Problem and Research Objectives

The problem of optimally managing a single aquifer has been widely studied and addressed in the groundwater economics literature. In many real-world circumstances, however, multiple sources of groundwater are available to supply a particular consumption region. For example, the Honolulu Board of Water Supply (HBWS) currently extracts groundwater from the Pearl Harbor and Honolulu aquifers simultaneously and pumps this water into an interconnected pipeline serving both consumption districts. Inasmuch as such a situation requires a management tool to integrate extraction, distribution, and consumption from both sources, our primary objective is to develop an operational economic-hydrologic model to solve for the optimal paths of extraction over time.

To analyze the principle of optimal groundwater use when water may be extracted from two sources we build on previous research that estimated the efficient water allocations in Pearl Harbor (Krulce et al. 1997) and in Honolulu (Pitafi and Roumasset 2009). Using updated consumption and pumping data, in combination with the pricing scheme implemented by HBWS in 2006, we first reassessed each aquifer independently. In particular, supposing that each water district is independent, we solved for the optimal allocation of water over space and time.[1] The results are of interest inasmuch as self-sufficiency is currently being considered as a viable groundwater management strategy for the region. We then constructed and implemented a multiple-aquifer model to estimate the optimal joint allocation of water from the two aquifers. Results from a numerical simulation provide the optimal price and head paths for each aquifer and, thus, the date at which, based upon current costs, desalination should be implemented.

Finally we considered the possible impact of future climate change on our groundwater resources. To date economic models of groundwater have assumed that weather patterns in Hawaiʻi will remain constant. Since the island of Oʻahu obtains nearly 90% of its freshwater from groundwater stocks, any substantial decrease in aquifer recharge resulting from climate change will have a large impact on consumers. Although regional climate-change models are still not fully developed, incorporating such models into a hydrologic-economic framework is a promising area for future research. In the current study we simulate the impact of climate change by estimating the optimal allocation of water under various net-recharge scenarios.

[1] By "independent" we mean that extracted water is consumed in the immediate geographical vicinity of the aquifer, i.e. imports/exports between Pearl Harbor and Honolulu consumption districts are not permitted.

Methodology

The Model

We develop and solve an optimal control[2] model that integrates extraction, distribution, and consumption from multiple groundwater sources. In practice a resource manager would choose the rate of extraction from each aquifer and the rate of desalination in order to maximize the present value of net social benefits, i.e. the benefits from water consumption minus the costs of extracting and distributing the water, as follows:

$$\underset{q_t^{ij},b_t^i}{Max}\sum_{t=0}^{\infty}\rho^t\left\{\sum_i\left(\int_0^{\sum_j q_t^{ij}+b_t^i} D_i^{-1}(x,t)dx-\sum_j\left(q_t^{ij}[c_j(h_t^j)+c_d^i]\right)-b_t^i[c_b+c_d^i]\right)\right\}$$

subject to $\gamma_j[h_{t+1}^j-h_t^j]=f_j(h_t^j)-\sum_i q_t^{ij}$

$q_t^{ij}\geq 0, b_t^i\geq 0, h_t^j\geq h_{\min}^j \ \forall i,j$

where for each period *t*, aquifer *j*, and consumption category *i*, q_t^{ij} is the rate of extraction, b_t^i is the rate of desalination, $\rho\equiv(1+r)^{-1}$ is the discount factor, $D_i^{-1}(x,t)$ is the inverse-demand function, $c_j(h_t^j)$ is the marginal-extraction cost, c_d^i is the unit-distribution cost, c_b is the unit cost of desalination, γ_j is a height-to-volume conversion factor, h_t^j is the head level, $f_j(h_t^j)\equiv R^j-l_j(h_t^j)$ is the net-recharge function or natural recharge less leakage, and $h_{\min}^j$ is the minimum allowable head level.

We assume a constant elasticity demand function of the form $D_i(x_t^i,t)=\alpha_i e^{gt}(x_t^i)^{-\eta}$, where η is the elasticity. Demand grows over time at rate g and the demand coefficients α_i are calculated using 2006 price and quantity data. Net recharge decreases as the head level increases because a higher head means more pressure along the freshwater-saltwater interface[3] over a larger area, which translates to more leakage. Thus the functions f_j are decreasing and concave in head levels, i.e. $f_j'<0$ and $f_j''\leq 0$. Extraction costs depend on the distance water must be lifted and the cost of the energy required to do so. Inasmuch as increasing the head level reduces the lift, the extraction-cost function is modeled as increasing and convex (linear) in head levels, i.e. $c_j'>0$ and $c_j''\geq 0$.

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[2] Optimal control is a standard mathematical technique used to solve dynamic optimization problems. See e.g. Chiang (1999).

[3] This characteristic is specific to coastal aquifers but the general methodology is still applicable to other types of groundwater resources.

In solving the model, we derive the following efficiency price rule:

$$p_t^i \le \pi_t^{ij}, \qquad \text{if } <, \text{ then } q_t^{ij} = 0$$
$$p_t^i \le c_b + c_d^i, \qquad \text{if } <, \text{ then } b_t^i = 0$$

where $\pi_t^{ij} \equiv c_j(h_t^j) + c_d^i + \rho\gamma_j^{-1}\lambda_{t+1}^j$ is the total marginal cost of a unit of water extracted from aquifer *j*. In other words, if the price for category *i* is less than the total marginal cost of a unit of groundwater extracted from aquifer *j* for consumption in *i*, then no water is extracted for that purpose. Since it is never the case that zero water is consumed, it must be that $p_t^i = \min(\pi_t^{i1}, \pi_t^{i2}, ..., \pi_t^{iJ}, c_b + c_d^i)$. Consequently $p_t^i = \pi_t^{im}$ when aquifer *m* is being used $(q_t^{im} > 0)$ and $p_t^i = \pi_t^{im} = \pi_t^{in}$, $\Delta p_t^i = \Delta\pi_t^{im} = \Delta\pi_t^{in}$ $(q_t^{im} > 0, q_t^{in} > 0)$ when aquifers *m* and *n* are being used simultaneously. A two-aquifer example is depicted in Figure 1 below.

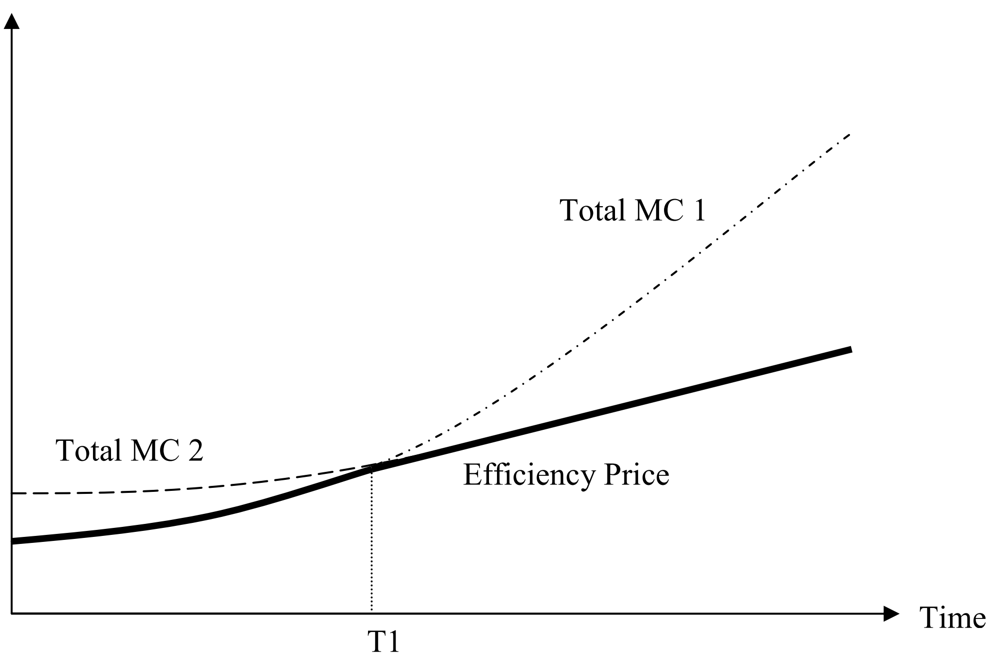

Figure 1: Efficiency Price Path with 2 Aquifers.

In this example, the total marginal cost (TMC) for aquifer 1 (TMC1) initially exceeds TMC2 so the price is determined by TMC1 and aquifer 1 is drawn down while aquifer 2 is built up. At T1, the price switches to TMC2 because aquifer 1 reaches its head constraint. The entire efficiency price path is characterized by the lower envelope of the two TMC curves.

Numerical Computations

The problem is solved using a forward-iterating algorithm. The initial and terminal conditions for the head level are known, as is the terminal price; growing demand ensures the implementation of the backstop at some point since the size of the aquifer system is finite and steady-state calculations confirm that the minimum-allowable-head constraints become binding. Thus the optimal path will be determined once we know the correct initial shadow prices.

One way to approach the problem is to use a shooting method. Educated guesses are made for the initial shadow prices. The first-order conditions derived from the optimal control problem allow one to then solve for the shadow prices in the following period. Once the period 2 shadow prices are determined the price and therefore the rates of extraction can be ascertained for the current period. The rates of extraction reveal the head levels in the next period via the equation of motion and the whole process can be repeated using the period 2 head levels and shadow prices as the new starting point.

Eventually one of the terminal conditions is reached. If one or more of the other terminal conditions is inconsistent then the initial guesses for the shadow prices must have been wrong. The guesses must be adjusted and the process repeated until all of the initial and terminal conditions are satisfied for the head level of each aquifer and the price.

Principle Findings and Significance

Independent Aquifer Management

Under independent management, desalination is optimally implemented for Pearl Harbor after 148 years and the net present value gain of switching from status quo pricing to optimal but independent pricing is 8.2% of the status quo welfare (Figure 2). In the case of Honolulu, desalination becomes optimal after 9 years and the net present value gain of switching from status quo to efficiency pricing is 44% of the status quo welfare (Figure 3). These cases show that the present value of optimal management is highly sensitive to water scarcity. They also show that independent management is inefficient. For example, the efficiency price for Honolulu would be $7.43/thousand gallons after only 9 years, while the total marginal cost for groundwater from Pearl Harbor at the same time is only $0.32/thousand gallons.

Joint Management

Under optimal management of the two aquifers, desalination is implemented after 100 years and the net present value gain of switching from independent to joint management is 44% of the aggregated independent present values (Figure 4). Transitional dynamics derived from the multiple aquifer model indicate that optimal extraction switches from exclusive use of Pearl Harbor aquifer, to simultaneous use of both aquifers, to maximum sustainable yield (MSY) from both aquifers supplemented by desalination. The results indicate that Pearl Harbor aquifer should be drawn down to its MSY head level in the near future and that there should be substantial accumulation in the Honolulu system of aquifers of up to 30 feet before it is ultimately drawn down to its MSY level.

Groundwater Management and Climate Change

With a 10% reduction in natural recharge (R) the optimal desalination time is 17 years sooner than in the baseline case and the present value of the lost recharge is $432.1 million. With a 30% reduction, the lost value exceeds $1 billion (Table 1). The recharge scenarios are meant to simulate decreased precipitation and increased frequency of extreme events leading to increased runoff, both of which are expected results of climate change. The large potential losses thus strengthen the case for watershed conservation.

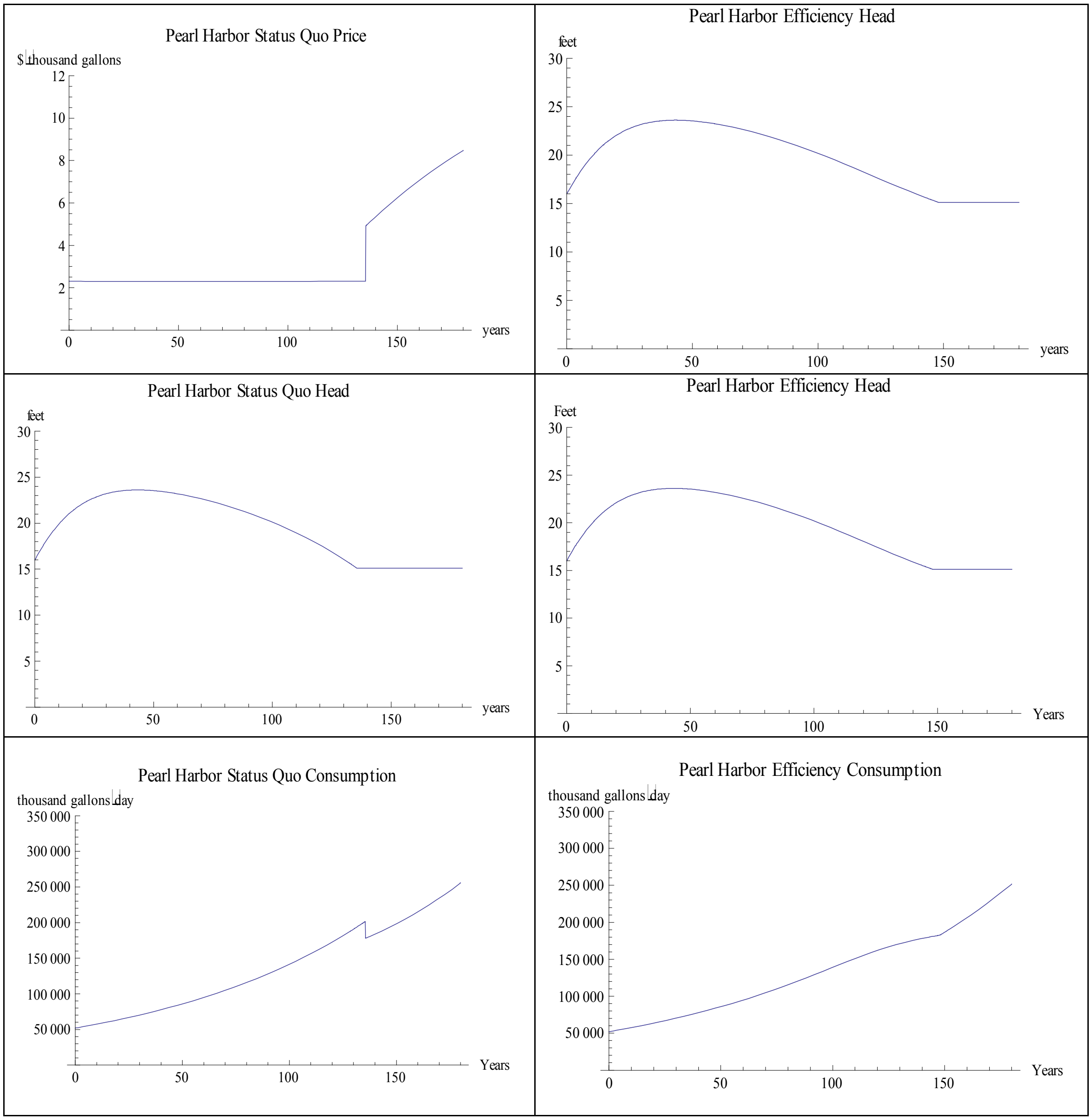

Figure 2: Status Quo and Efficiency (Self-Sufficient) Management for Pearl Harbor

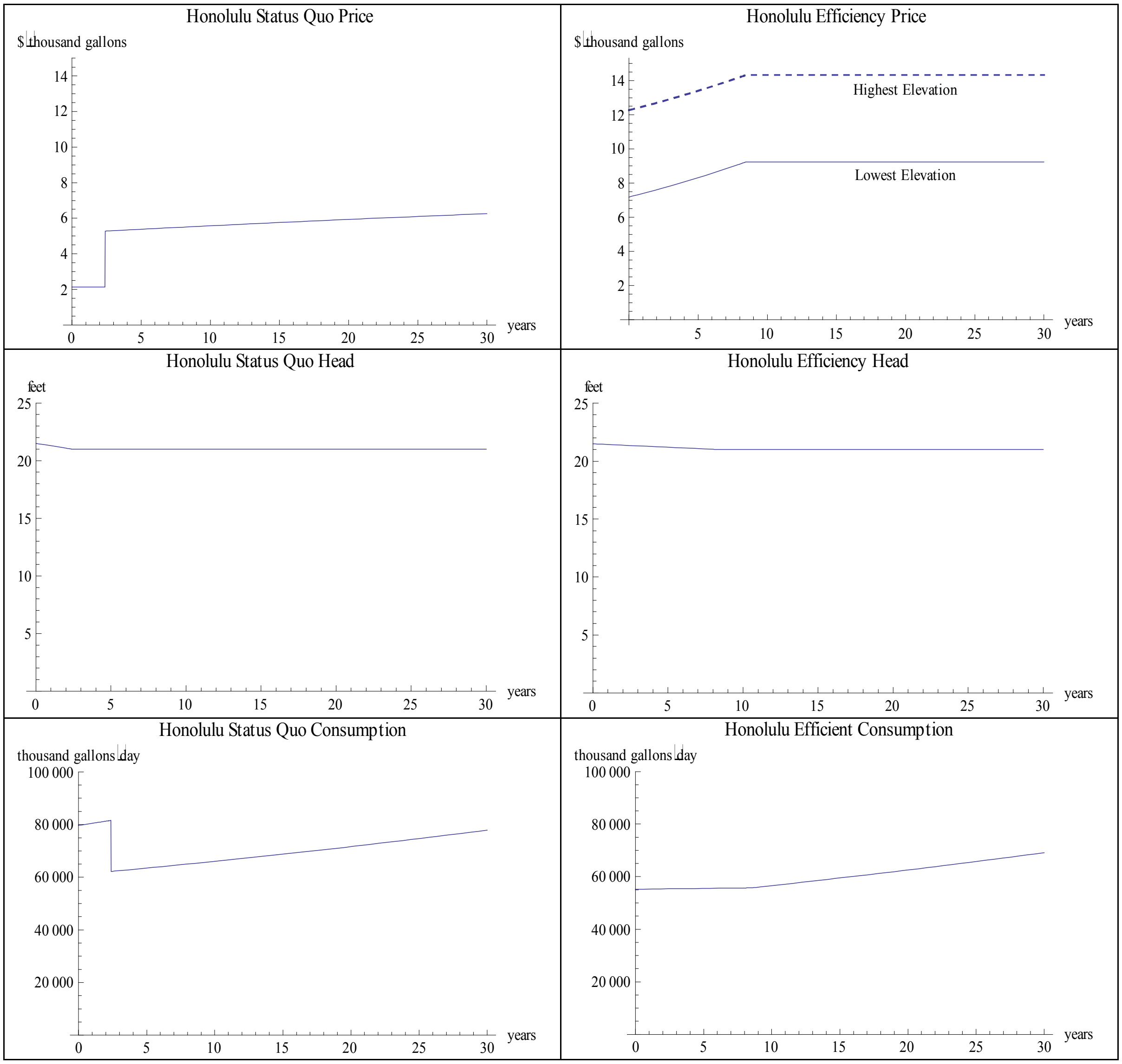

Figure 3: Status Quo and Efficiency (Self-Sufficient) Management for Honolulu

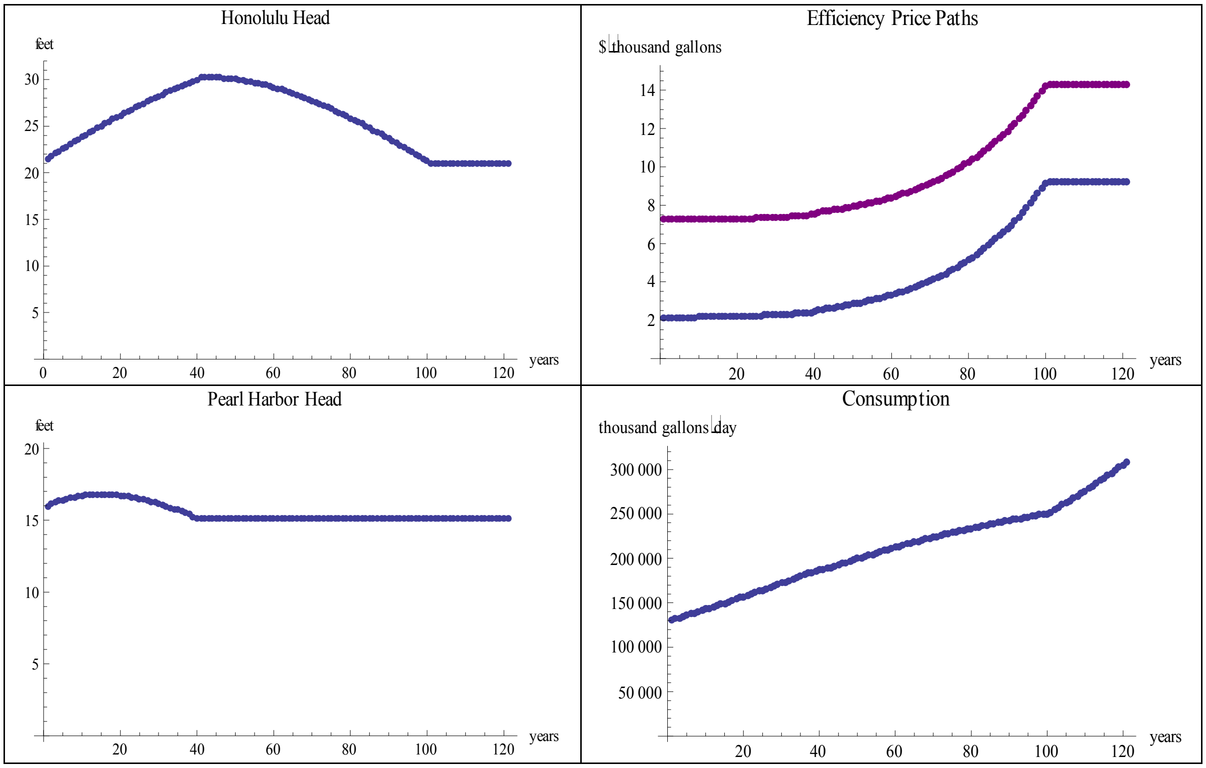

Figure 4: Head, Price, and Consumption Paths Under Joint Optimization

Scenario	τ_1 (yrs)	T (yrs)	PV (million $)	PV lost recharge (million $)
Baseline	40	100	$12,047.80	—
$g = 2\%$	29	58	$15,912.90	—
90% R	24	83	$11,615.70	$432.10
80% R	12	63	$11,492.70	$555.10
70% R	8	46	$10,942.70	$1,105.10
$g = 2\%$ & 90% R	20	49	$16,713.70	$686.90
$\eta = 0.5$	40	112	$10,457.80	—

Table 1. Sensitivity Analysis

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

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Determination of the Relationship between Biodiversity and Trophic Status of Wahiawa Reservoir

Basic Information

Title:	Determination of the Relationship between Biodiversity and Trophic Status of Wahiawa Reservoir
Project Number:	2008HI228B
Start Date:	3/1/2008
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Funding Source:	104B
Congressional District:	Hawaii 1st
Research Category:	Engineering
Focus Category:	Water Supply, Water Quality, Management and Planning
Descriptors:	Water Eutrophication, Biodiversity
Principal Investigators:	Tao Yan, Clark Liu

Publication

1. Lee, T.-C., C.C.K. Liu, and T. Yan. 2009. Bio-productivity and bio-diversity in a lake subject to development stress. *Proceedings of CTAHR Research Symposium, April 3–4, 2009, University of Hawai'i at Mānoa.*

Problem and Research Objectives

Nutrient enrichment in rivers and lakes in the United States has been an evolving phenomenon over the past three decades (Smith et al. 1987). Point-source contributions, such as wastewater discharge, have largely been effectively controlled and substantially reduced. However nonpoint-source contributions, such as urban and agricultural run-off, are increasingly responsible for water eutrophication problems across the country (Litke 1999). Given the complex nature of nutrient dynamics in inland waters, accurate and timely trophic-state assessment is important for efficient and cost-effective regulatory and remediation actions (Alexander et al. 2000).

Traditional trophic-state assessment methods are based on either single physical/chemical parameters or composite indices of single parameters. Single trophic parameters, such as Chlorophyll *a* content (Chl *a*), diurnal dissolved oxygen variation, total nitrogen (TN), and total phosphorus (TP), are easy to measure but usually do not address the multi-dimensional nature of the trophic status of inland waters. The current composite indices, such as the Carlson trophic status index (TSI) (Carlson 1977, Dodds et al. 1998), have proven to be more effective than the single parameters because of their integration of multiple parameters.

Despite their widespread use in water resource management, traditional trophic state assessment methods for inland waters do not address the interactions between abiotic factors and biotic factors. Understanding these interactions, in particular how nutrient loads affect microbial communities, is important for improving the predictive capabilities of existing trophic-assessment methods.

Advances in molecular tools, including the availability of the 16S/18S ribonucleic acid (RNA) gene-based clone library and microbial community genetic fingerprinting, have enabled cultivation-independent surveys of microbial species biodiversity (Pace et al. 1985, Woese and Fox 1977). The molecular biodiversity, i.e. the estimated microbial species richness and evenness (Hong et al. 2006), is directly influenced by interactions between the biotic and abiotic factors of the water environments. Therefore, theoretically, the interactions between the biotic and abiotic factors can be used to predict the possible eutrophication of inland waters.

To date, minimal work has been reported regarding the use of molecular tools to study the microbial communities of inland waters with differing tropic states (Jardillier et al. 2005, Lefranc et al. 2005). There is little documentation as to how changes in the trophic states of such waters affect their biodiversity and vice versa. Therefore, the primary research objective of this project was to conduct laboratory experiments to simulate trophic changes at the Wahiawā Reservoir (Oʻahu, Hawaiʻi) and investigate the relationship between trophic states and microbial biodiversity. The working hypothesis is that the eutrophication process, i.e., the transition from oligotrophic to eutrophic and to hypertrophic, corresponds to a decrease in microbial biodiversity.

These trophic transitions will be studied in lab-scale testing where eutrophication will be artificially simulated. The biodiversity of both bacteria and algae will be monitored using polymerase chain reaction (PCR)-denaturing gradient gel electrophoresis (DGGE) methods and analyzed using the Shannon H' (species richness) and E (species evenness) indices.

Methodology

Designing the lab-scale test apparatus. A flow-through lab-scale test apparatus (Figure 1) was constructed to study how lake productivity and biodiversity is influenced by nutrient inputs. The test apparatus was a rectangular tank with a total volumetric capacity of 15 L and a surface area of 0.045 m^2. Two types of artificial lights were tested: 1) compact cool-while fluorescent (Agrolight, Philips) and 2) metal-halide (Multi-Vapor Lamp, GE) lights. Metal-halide light sources were selected for the experiments because of the desirable light intensity range. A sterile growth medium was fed through the test system at flow rates designed to achieve hydraulic retention times (T_R) that were determined based on the Vollenweider model (Vollenweider 1968).

The test apparatus utilized diffused-air agitation to simulate completely stirred tank reactors. The air diffuser was installed at the bottom of the culture vessel to facilitate air-bubble agitation throughout the culture vessel. As well as keeping the culture media well agitated the diffused air also supplied dissolved CO_2 for algal growth.

Operation of the lab-scale test apparatus. Total phosphorus (TP) was used as the limiting nutrient controlling different trophic states (i.e., oligotrophic, mesotrophic, and eutrophic) within the test apparatus. Determination of TP concentrations and other operational conditions, including T_R, overflow rate (Q/A), and TP loading (TP/surface area) were based on the Vollenweider model (Table 1) (Vollenweider 1968).

The Bold's basal medium (BBM) (Bold 1949) was adopted for algae cultivation to create the limited-nutrient condition of reactive phosphorus. TP concentrations tested were 5µM, 15µM, and 60µM of K_2HPO_4. The modified BBMs were autoclave sterilized at 121°C for 20 min before use. The test apparatus was continuously irradiated at 8900 W/m^2 with metal-halide lamps. The inoculums of algae were obtained from the Wahiawā Reservoir and added to the three different BBMs using a 10% by volume inoculum-to-BBM ratio.

Analytical methods. Parameters to be monitored during the field investigation and laboratory experiments include algae cell numbers, Chl *a*, dissolved oxygen (DO), pH, TN, total organic carbon (TOC), TP and reactive phosphorus, total solids (TS), and turbidity.

The quantification of Chl *a* was achieved by adsorption measurements at three different wave lengths (664, 647, and 630 nm) using a spectrophotometer (DR/4000, HACH). Direct microscopy counting of algae cell numbers was accomplished using a hemocytometer (Hausser Scientific, Horsham, PA) and a bright-field microscope. Concentrations of TP and reactive phosphorous were determined using a PhosVer 3 kit and a DR/4000 Hach spectrophotometer following the procedure provided by the manufacturer. TN was measured using a TOC-VCPN instrument (Shimadzu Corporation, Kyoto, Japan) based on the oxidative combustion-chemiluminescence mechanism. Water-sample turbidity was measured using a Model 2100N Laboratory Turbidimeter (HACK) with a working range of 0 to 4000 Nephelometric Turbidity Units (NTU). Total carbon (TC), inorganic carbon (IC), and TOC in water samples were measured using a TOC-VCPH/CPN instrument (Shimadzu Corporation, Kyoto, Japan). Total suspended solids (TSS) was determined based on the Standard Method 2540 D (A.P.H.A. 1985). Glass fiber filters (0.45 µm, 47 mm diameter; Pall, East Hills, NY) were used to retain suspended solids from water sample. Filters containing suspended solids were processed by repetitive drying at 105°C, cooling, desiccating, and weighting until weight changes were less than 4% of the previous weight. Total dissolved solids (TDS) of water samples were determined using Standard Method 2540C (A.P.H.A. 1985). Filtrates from glass fiber disks (0.45 µm, 47 mm diameter) were placed in a pre-weighed drying vessel. After evaporated to dryness on a steam bath, the drying vessels were further heated in an oven at 180˚C ±2˚C. After being cooled in a desiccator to ambient temperature, final weights were determined to calculate the amount of dissolved solids. An Orion® 720A+ Dual Channel pH/ISE Meter (Thermo; Waltham, MA) was used for pH measurements. A YSI 58 DO meter (YSI, Inc., Yellow Springs, Ohio) was used for DO measurements.

Molecular biology analysis. The overall scheme of using a molecular approach to characterize prokaryotic and microeukaryotic biodiversities is illustrated in Figure 2. PCRs were conducted on an iCycler (Bio-rad, Hercules, CA) to amplify the small subunit ribosomal ribonucleic acid (rRNA) genes (i.e., 16S rRNA or 18S rRNA for prokaryotes and eukaryotes, respectively). The amplified rRNA genes were then visualized using DGGE. Computer-aided image analysis was performed to identify gel bands representing distinct microbial populations and Shannon index values were calculated to describe the biodiversity of the water samples. Experiments are ongoing to sequence individual DGGE bands and construct a 16S rRNA gene library to determine the exact phylogeny of the populations.

Principal Findings and Significance

The lab-scale test apparatus successfully generated test samples with different tropic states. The development of the different trophic states corresponded well with predictions based on the Vollenweider model.

Figure 3 shows the effects of varying the TP (the limiting nutrient) on the bioproductivity of the test reactors. Steady state within the different modified/inoculated BBMs, indicated by the maintenance over time of consistent Chl *a* concentrations, was reached within ten days in all three tests. The test reactors receiving smaller amounts of TP showed lower productivities as indicated by lower concentrations of Chl *a*. Repetitive experiments generated similar results (data not shown). The algal growth kinetic parameters and other physical and chemical parameters are shown in Table 2.

The bacterial microbial communities in the three different test reactors showing different bioproductivities are shown in Figure 4A and the corresponding microeukaryotic communities are shown in Figure 4B. In the DGGE images, each individual band represents a distinct microbial population. It can be seen that once the test media reached equilibrium the microbial communities stabilized. After the DGGE images were processed to enumerate the distinct bands (i.e different microbial populations), Shannon diversity indices were calculated for both prokaryotic and microeukaryotic communities (Tables 3 and 4). Each lane in the DGGE images represents one separate microbial community and the corresponding H' value describes biodiversities.

Under the three different experimental conditions prokaryotic biodiversity graphs a concave-curve-graph tendency along trophic-level gradient This tendency resulted from many ecological processes (e.g., affinity for nutrients, competition, and predator-prey interactions). The rarefaction analysis for the microeukaryotic communities indicate that the mesotrophic bioreactor's diversity is higher then that of the other two trophic levels.

Table 1.

Experimental parameters of bioreactors based on a Vollenweider plot dividing the three categories of trophic levels

	Flow Rate (ml/min)	TP (µg-P/L)	T_R (day)	Overflow rate (m/yr)	TP areal loading ($g/m^2/yr$)
Oligotrophic	2.6	5	4.3	29.2	0.15
Mesotrophic	1.5	15	7.2	17.5	0.37
Eutrophic	0.9	60	12.4	10.5	0.63

Table 2.

Algal-growth kinetics and some physical and chemical properties of the three test media with different trophic states

Parameter	Oligotrophic	Mesotrophic	Eutrophic
Biomass (mg Chl *a*/m^3) [a]	7	12	66
Retention time (days)	4.3	7.2	12.3
Rates of bioproductivity (mg Chl *a*/m^3 day)	1.6	1.7	5.3
TN (mg/L)	55.69	56.69	59.15
TP (P-µg/L)	3.30	16.50	34.65
TDS (mg/L)	483.33	485.56	513.89
TSS (mg/L)	0.31	3.94	4.47
TOC (mg/L)	25.66	26.89	30.96
TC (mg/L)	28.45	30.31	36.04
IC (mg/L)	2.79	3.42	5.09
Chl *a* (µg/L)	7	12	66
Turbidity (NTU)	0.46–0.67	1.55–1.77	3.61–6.43
Cell (1/ml)	0.00	0.00	0.00
Phosphate (Reactive, µg-P/L)	17.33	13.20	12.38
Uptake Phosphate (Reactive, µg-P/L)	3.30	6.60	26.40

[a]: Chl *a* is content of Chlorophylls *a*

Table 3.

Diversity indices based on DGGE banding data analysis of 16S rRNA gene fragments

Lane	Band numbers	$\sum p_i Ln(p_i)$	H'	E
1	22	-3.087	3.087	0.9988
2	14	-2.630	2.630	0.9966
3	13	-2.553	2.553	0.9953
4	15	-2.704	2.704	0.9986
5	19	-2.932	2.932	0.9957
6	18	-2.879	2.879	0.9959
7	19	-2.942	2.942	0.9990
8	19	-2.942	2.942	0.9990
9	14	-2.629	2.629	0.9961
10	20	-2.991	2.991	0.9983

Table 4.

Diversity indices based on DGGE banding data analysis of 18S rRNA gene fragments

Lane	Band numbers	$\sum p_i Ln(p_i)$	H'	E
1	18	-2.861	2.861	0.9899
2	21	-2.965	2.965	0.9739
3	24	-3.101	3.101	0.9757
4	23	-3.022	3.022	0.9638
5	27	-3.202	3.202	0.9714
6	18	-2.799	2.799	0.9684
7	24	-3.074	3.074	0.9673
8	24	-3.074	3.074	0.9673
9	18	-2.783	2.783	0.9629
10	27	-3.208	3.208	0.9732

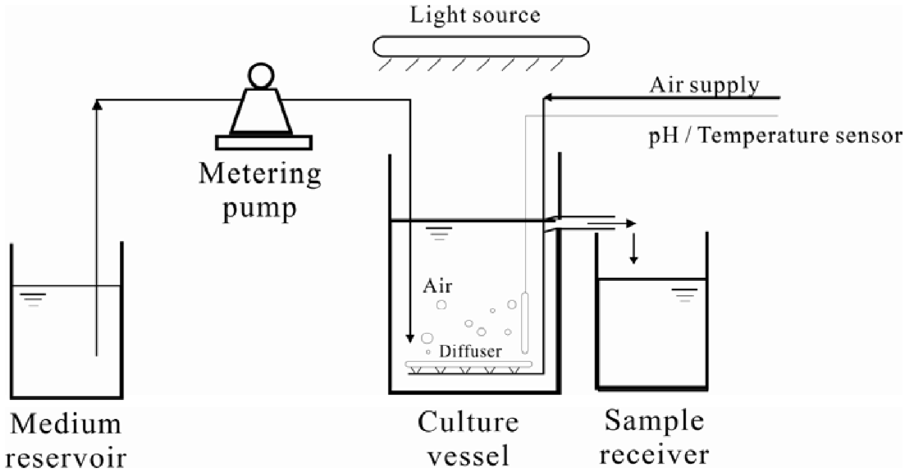

Figure 1.

Schematic of a flow-through lab-scale test apparatus used to study lake nutrient inputs, biodiversity, and productivity.

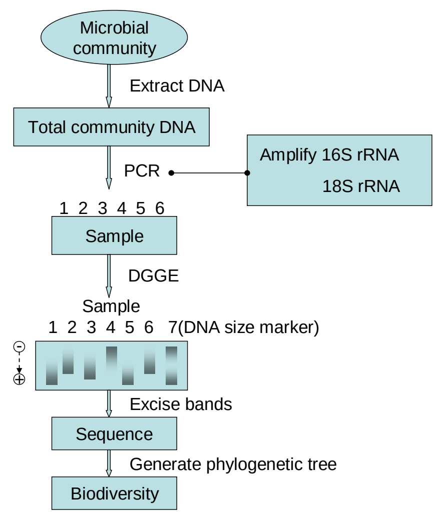

Figure 2.

Flow chart illustrating the PCR-based biodiversity analysis of a microbial community.

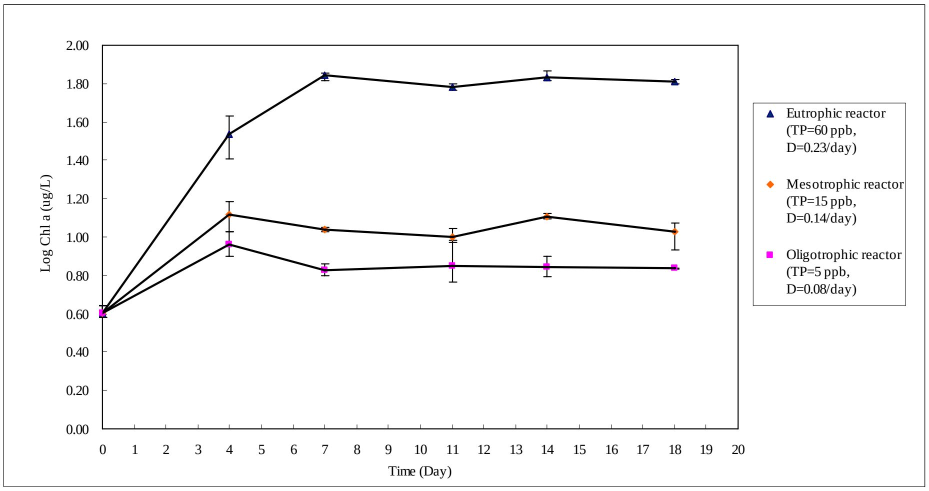

Figure 3.

Concentrations of Chl *α* over time in three test media receiving different concentrations of TP.

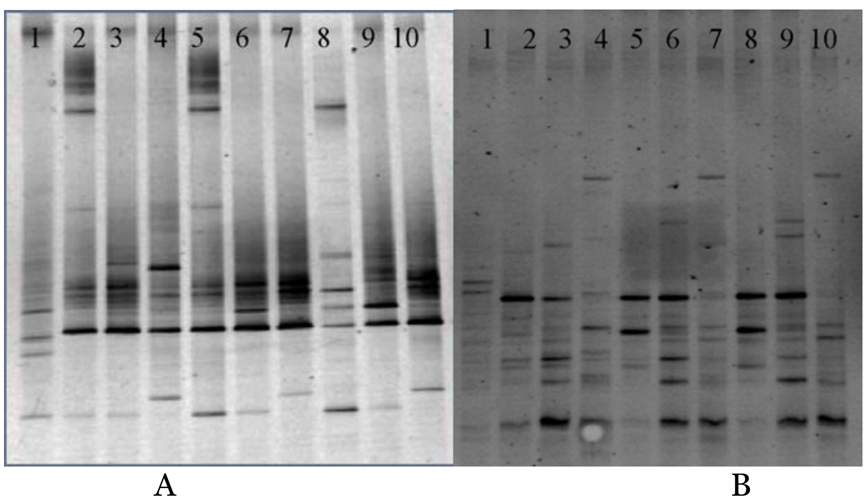

Figure 4.

(A) Bacterial communities revealed by 16S-rRNA gene-based DGGE analysis.

Lane 1: the original inoculum from the Wahiawā Reservoir.
Lanes 2–4, 5–7, and 8–10 are for the oligotrophic, mesotrophic, and eutrophic test reactors, respectively, at various times during the experiment.

(B) microeukaryotic communities revealed by 18S rRNA gene-based DGGE analysis.

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Modeling of Humidification-Dehumidification (HDH) Seawater Desalination Systems Driven by Solar Energy

Basic Information

Title:	Modeling of Humidification-Dehumidification (HDH) Seawater Desalination Systems Driven by Solar Energy
Project Number:	2008HI231B
Start Date:	3/1/2008
End Date:	2/28/2009
Funding Source:	104B
Congressional District:	Hawaii 1st
Research Category:	Engineering
Focus Category:	Water Supply, Treatment, None
Descriptors:	Freshwater supply, seawater desalination, humidification-dehumidification
Principal Investigators:	Weilin Qu

Publication

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 Hawai‘i because of the high energy cost. The primary energy source used in Hawai‘i 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 Hawai‘i. While its geographical location makes electricity and high-grade petrochemical-based thermal energy expensive in Hawaiʻi, 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, S.C. Wang, Xie, Z. Wang, and Li (2005); Shaobo et al. (2005); Xiong, S.C. Wang, Z. Wang, Xie, Li, and Zhu (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 when air presents in water vapor.

Klausner and co-workers at the University of Florida recently described (Klausner et al. 2004; Klausner et al. 2006; Li, Klausner, Mei, and Knight 2006; Li, Klausner, and Mei 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.

Effective design and optimization of solar-energy-driven HDH seawater desalination systems requires a fundamental understanding and accurate prediction 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 2008 U.S. Geological Survey State Water Resources Research Institute Program (WRRIP2008) constitutes the Phase I of the research program. The focus of the Phase I research is on developing theoretical models to describe thermal and hydraulic characteristics of the two most critical system components—the evaporator and the condenser.

Methodology

Figure 1 shows a simplified schematic diagram of the proposed HDH seawater desalination system driven by solar energy. The system is composed of three main fluid-circulation subsystems, identified as seawater, air/vapor, and freshwater.

In the seawater subsystem, seawater is introduced into the system from a seawater reservoir using a pump (a). The seawater is pumped through a solar water heater (b) where its temperature is brought to a higher level. The seawater is then sprayed into the top of an evaporator (c) and is in direct contact with air that is pumped into the evaporator from the bottom. A portion of the seawater evaporates and thus humidifies the air. The seawater not evaporated in the evaporator is collected at the bottom of the evaporator and discharged back to the seawater reservoir (d) as high-salt brine.

In the air/vapor subsystem, air is pumped into the bottom of the evaporator (c) using a forced-draft blower. After leaving the evaporator, the air is drawn into a condenser (e) where it is in direct contact with freshwater that is sprayed into the top of the condenser. Water vapor condenses out from the air into the freshwater. The resulting lowered-humidity air is directed back to the evaporator (c) and used repeatedly.

In the freshwater subsystem, the water gains heat and mass in the condenser (e). After being discharged from the condenser (e) it is cooled in a freshwater cooler (f) by the incoming cold seawater. The freshwater cooler (f) also serves as a heat exchanger for the purpose of preheating the seawater, helping to reduce the amount of solar radiation needed in the solar water heater (b) to bring the seawater to the desired evaporator inlet temperature. Finally, a portion of the freshwater is directed back to the condenser (e) to condense water vapor from the humid air. The remaining portion of the freshwater is the production.

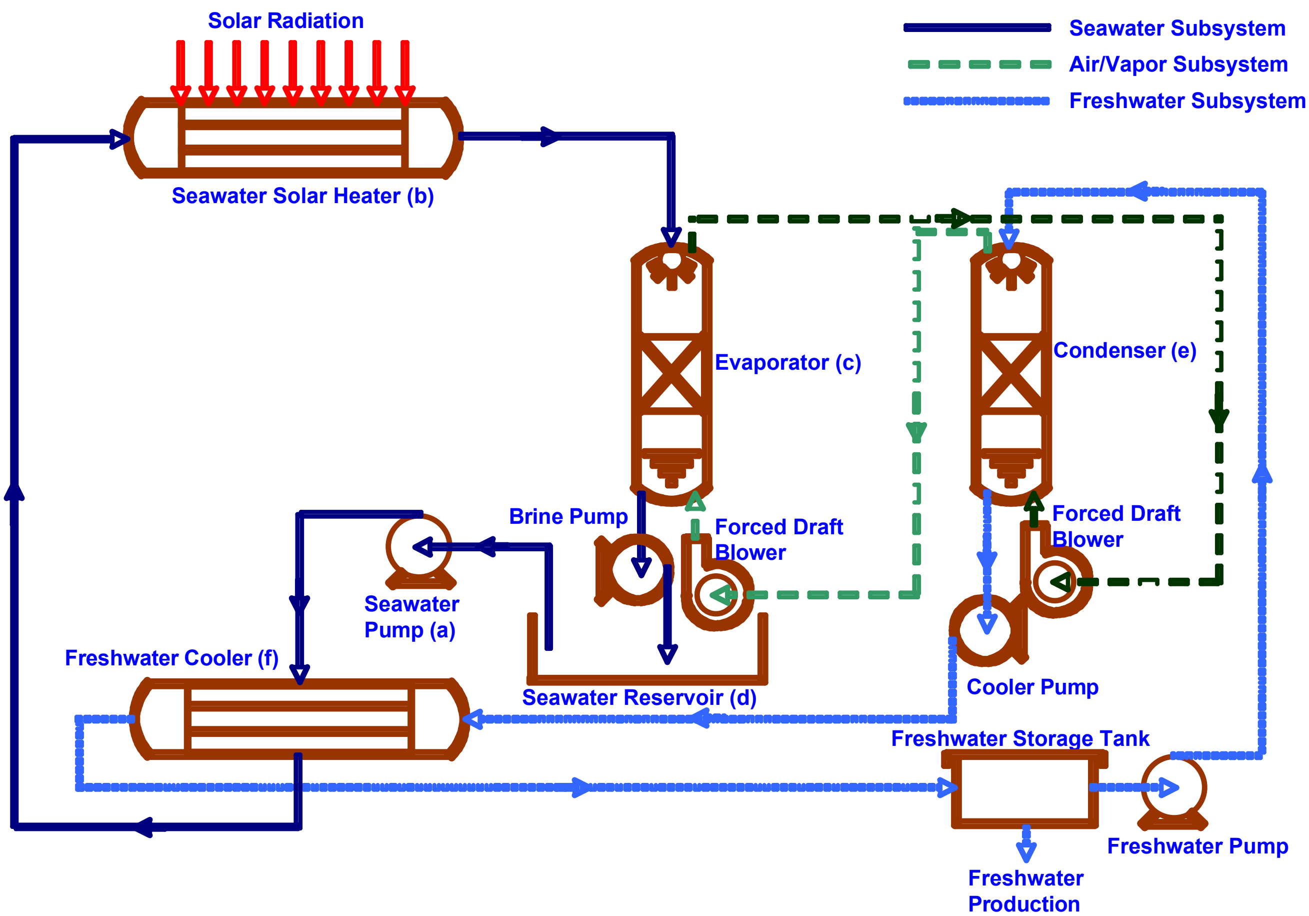


Figure 1. Flow diagram of solar-energy-driven HDH desalination system.

As illustrated in Figure 1, the evaporator (c) and the condenser (e) are the most critical components and dominate the system performance. The evaporator is fitted with a porous tower-packing material, in this case HD Q-PAC® structured media (Lantec Products, Inc., Agoura Hills, CA), providing an ultra-high surface area. The hot seawater that is sprayed into the top of the evaporator forms a water film on the surface of the tower-packing material while gravity-flowing downward along the evaporator. The cold dry air is pumped into the evaporator at the bottom and blown upward into and through the wetted tower-packing material. The direct contact between the hot seawater and the cold, dry, air leads to a heat and mass-transfer process between the water and the air.

The result of this heat and mass-transfer process is that a portion of the seawater evaporates and thus humidifies the air and the air temperature increases and the seawater temperature decreases. Taking advantage of solar radiation to preheat the seawater before it enters the evaporator increases the freshwater production. As both the water-evaporation and air/humidity ratio increase with increasing temperature, higher seawater temperatures lead to increased freshwater production.

The condenser has a structure similar to that of the evaporator, i.e., it is a tower fitted with a porous tower-packing material, in this case also HD Q-PAC® structured media. The humid warm air in the evaporator is pumped into the bottom of the condenser and blown upward. The air then comes into direct contact with cold freshwater being sprayed into the top of the condenser. As a result of a second heat and mass-transfer process, opposite to that in the evaporator, air temperature decreases and the water vapor condenses out from the air into the freshwater. The water condensate constitutes the freshwater production from the system.

In the test project a one-dimensional control-volume-based theoretical approach was adopted to model the aforementioned heat and mass-transfer processes in the evaporator and the condenser, respectively. Applying the mass-conservation principle to the counter-current air/water two-phase flow, the energy-conservation principle to the liquid film, and the energy-conservation principle to the air core led to a group of governing differential or algebraic equations for the respective transport processes. These equations were solved numerically to yield a detailed description of the working characteristics of the evaporator and condenser.

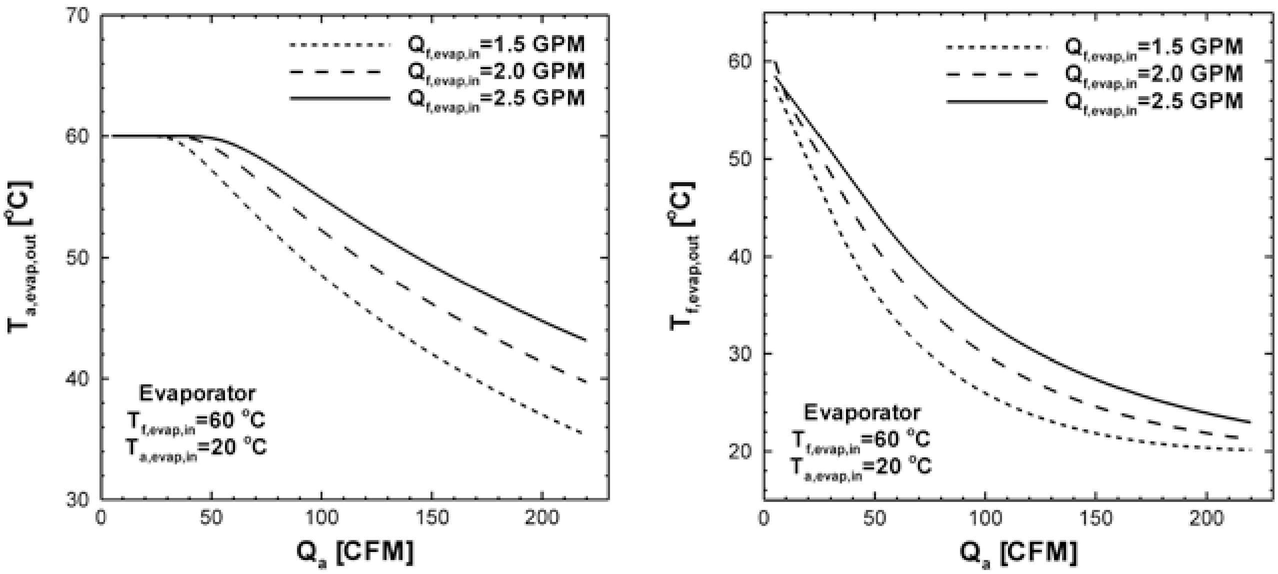
Principal Findings and Significance

A theoretical model has been developed in this project that is able to predict the net-freshwater production of an HDH system under different operating conditions. The model is also able to provide detailed description of the temperature and humidity-ratio distributions in the critical system components of evaporator and condenser.

The accuracy of the model is now to be assessed by comparing the model predictions with experimental results from an ongoing experimental study. The experimental study is currently supported by the 2009 U.S. Geological Survey State Water Resources Research Institute Program (WRRIP2009) and constitutes Phase II of the research program. Upon validation, the model will provide an essential tool for the effective design and practical implementation of solar-energy-driven HDH seawater desalination systems.

Sample results from the model are presented below. Variables are defined as follow:
Q_a represents the air flow in cubic feet per minute (CFM);
T_a represents the air temperature in degrees Celsius (°C);
Q_f represents the water flow in gallons per minute (GPM);
T_f represents the water temperature in degrees Celsius (°C);
"ω" indicates the air/humidity ratio;
The subscript "evap" indicates the evaporator;
The subscript "cond" indicates the condenser;
The subscript "in" indicates an inlet;
The subscript "out" indicates an outlet;
The subscript "prod" indicates production.

Figures 2 and 3 show the predicted results for a representative evaporator whose tower-packing material section is 0.25 m in diameter and 1 m in height. The seawater-inlet temperature at the top of the evaporator is set to be 60°C and the air-inlet temperature at the bottom of the evaporator is 20°C. Figures 2(a) and 2(b) show the predicted variations of outlet temperatures of air and seawater versus the cold-air flow, respectively, for the three seawater flows of 1.0, 2.0, and 2.5 GPM. As expected, the air- and seawater-outlet temperatures decrease with increasing cold-air flows and increase with increasing hot-seawater flows. Figure 3 shows the predicted air outlet humidity ratio as a function of the cold-air flow for the three seawater flows of 1.0, 2.0, and 2.5 GPM.



(a) (b)

Figure 2. Predicted outlet temperatures vs. cold-air flow for an evaporator: (a) air and (b) seawater.

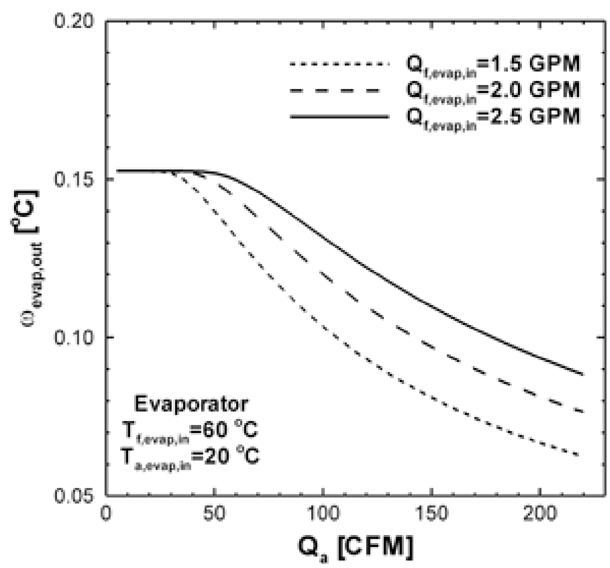


Figure 3. Predicted air-outlet humidity ratios vs. cold-air flow for an evaporator.

Figures 4–7 show the predicted performance of a condenser that has identical dimensions and structure as those of the evaporator. The air-inlet conditions at the bottom of the condenser correspond to the air-outlet conditions under an evaporator hot-seawater flow of 2.0 GPM. The freshwater inlet temperature at the top of the condenser is set to be 18°C. Figures 4(a) and 4(b) show the predicted outlet temperatures of air and freshwater as a function of the cold-air flow, respectively, for the three freshwater flows of 0.6, 0.8, and 1.0 GPM. Figure 5 shows the predicted freshwater production as a function of the cold-air flow for the three freshwater flows of 0.6, 0.8, and 1.0 GPM.

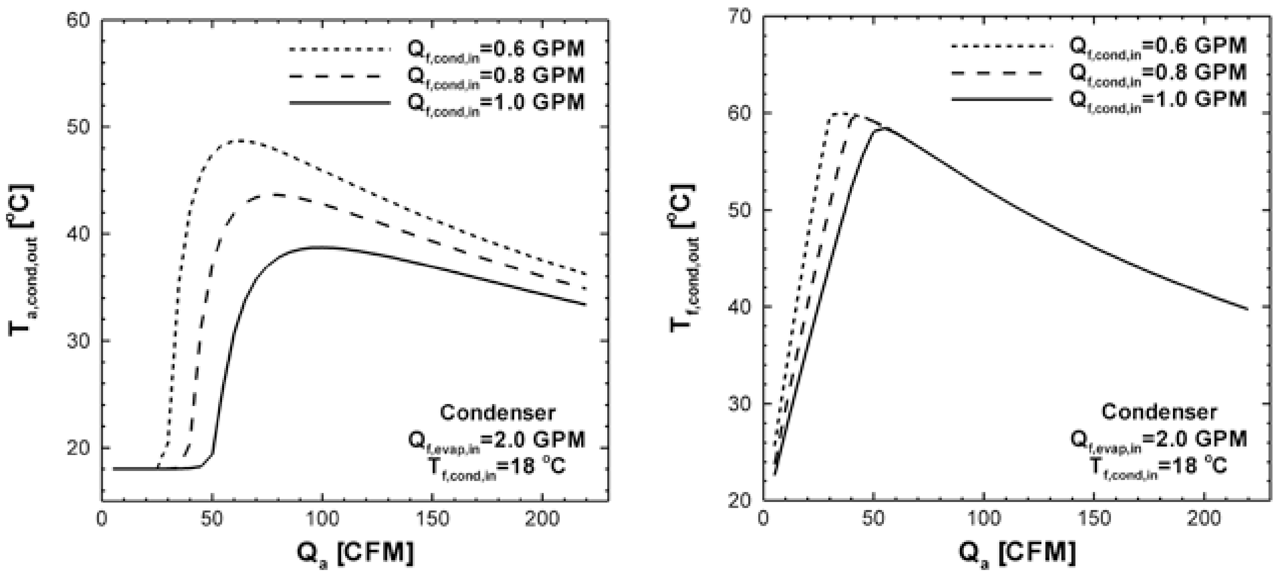


Figure 4. Predicted outlet temperatures vs. cold-air flow for a condenser: (a) air and (b) freshwater.

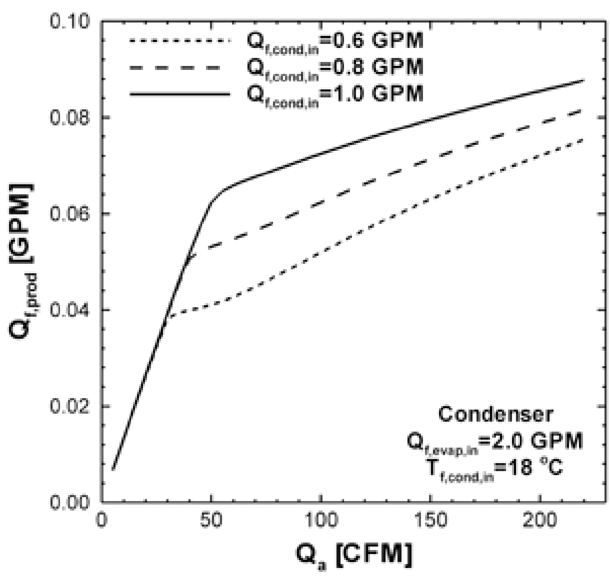
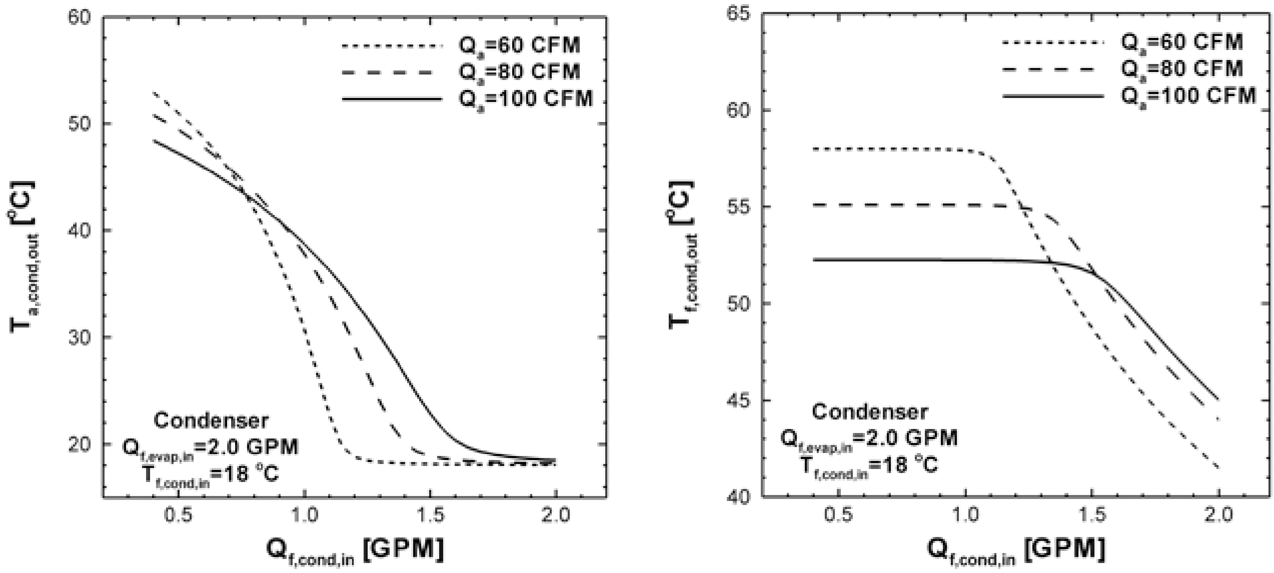


Figure 5. Predicted freshwater production vs. cold-air flow for a condenser.

Figures 6(a) and 6(b) show the predicted outlet temperatures of air and freshwater as a function of the freshwater flow, respectively, for the three cold-air flows of 60, 80, and 100 CFM. Figure 7 shows the predicted freshwater production as a function of the freshwater flow for the three cold-air flows of 60, 80, and 100 CFM.



(a) (b)

Figure 6. Predicted outlet temperatures vs. freshwater flow for a condenser: (a) air and (b) freshwater.

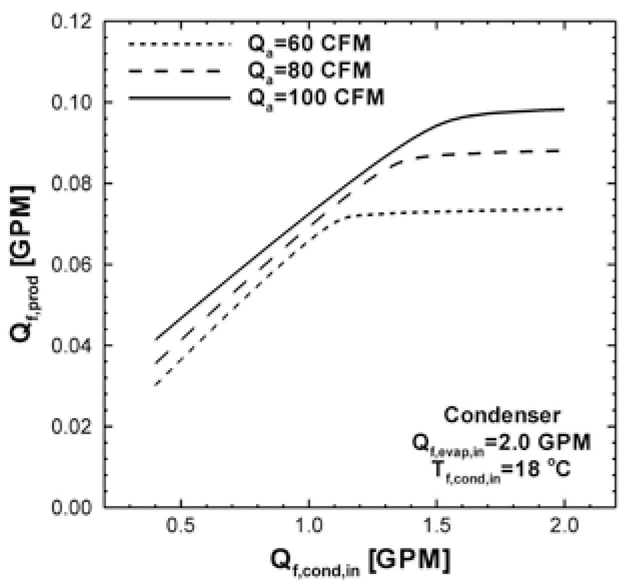


Figure 7. Predicted freshwater production vs. freshwater flow for a condenser.

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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
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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

Publication

Problem

Watershed-scale studies in Hawai‘i frequently require the integration of multiple aspects, including groundwater recharge, pollutant transport, sediment discharge, streambed erosion, and streamflow, of basin hydrology. Additionally the effects of rainfall variation or land-cover changes on any of these aspects may also 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 faced with the multiple concerns of improving coastal water quality, maintaining sustainable water supply, and restoring ecological integrity.

Existing watershed modeling studies in Hawai‘i include the Mānoa-Pālolo Stream on O‘ahu by Sahoo et al. (2006) and El-Kadi and Yamashita (2007), the Mākaha Valley on O‘ahu (Mair et al. 2007), and the Hanalei watershed on Kaua‘i (Polyakov et al. 2007). However these studies do not include groundwater processes—an aspect of interest because of the importance of the surface-water/groundwater interaction (e.g., Oki et al. 2006).

The primary factors controlling hydrologic processes in Hawai‘i watersheds are the temporal and spatial distribution of rainfall and runoff/infiltration characteristics. Steep/mountainous terrain generates substantial and powerful runoff and streamflow is highly variable, often producing very high peak flow rates in streams that have very 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) which are being correlated with raingages (e.g., Xie et al. 2006, Wang et al. 2008). The rainfall maps are 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. 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. Rainfall maps can be used to generate a rainfall-runoff model for the Kawela watershed to evaluate the accuracy of such models 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 that this approach would be expected to be applicable to other similar watersheds. The Kawela watershed is also a promising study site in part 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.

Objective

The objective of this study is to apply radar-inferred rainfall maps as input to a rainfall-runoff model for the Kawela, Molokaʻi, watershed to evaluate the accuracy of such a model for various climate and land-cover scenarios on streamflow and groundwater recharge.

Approach

The project will be addressed in two phases: 1) applying radar-inferred precipitation maps to a Kawela-watershed model, and 2) calibrating and refining the Kawela-watershed model so that it may be successfully adapted for differing rainfall/land-cover scenarios. Results will be published in the USGS Scientific Investigations Report series or in an alternative scientific journal.

Rainfall maps—The first challenge is to convert the extensive NEXRAD image dataset to a spatial grid of rainfall intensities which may then be transferred as a cumulative function to spatial daily rainfall values. The radar-inferred precipitation will be verified by correlation with existing raingages in and near the study area. Such correlation serves to validate the radar-inferred precipitation image data. 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 data for ca. one year exists from a raingage located in the middle of the eastern ridge of East Fork of Kawela Gulch. Several other raingages in the vicinity with longer records may also be used for verification (e.g., Waikolu raingage, State No. 540).

Kawela watershed model—Two watershed models can possibly be used: Precipitation-Runoff Modeling System (PRMS) is a modular, physically based, distributed-parameter rainfall-runoff modeling system developed to assess the effects of watershed characteristics on the hydrologic response (Leavesley et al. 1983). Groundwater-Surface Water Flow Model (GSFLOW) (Markstrom et al. 2008) is a coupled model that simulates surface-water (PRMS) and groundwater processes via a modular groundwater flow model (MODFLOW), which can be used for a more complex environment. If sufficient data is available GSFLOW will have the advantage of including more detail in the subsurface. Both models may be used to study discharge and recharge under different scenarios including changing climates and land covers.

The rainfall-runoff model will be calibrated with existing stream-discharge data. A streamgage with a sediment sampler at Kawela Gulch (USGS station 16415600) has measured daily stream-discharge values and daily suspended-sediment discharge and concentration since October 2004. Soil and vegetation coverages are readily available from the State of Hawai‘i GIS database. The vegetation coverage can be updated using the most recent mapping efforts by Jim Jacobi, USGS Pacific Island Ecosystems Research Center.

Meeting with the program developers of PRMS and GSFLOW in Denver will facilitate the model setup. Multiple fitting parameters, such as aquifer parameters, canopy transpiration, evapotranspiration, hydraulic parameters for soils, and rainfall/runoff ratios have to be estimated in the model calibration.

Application—Additional information will be identified regarding the spatial representation of rainfall and stream discharge to improve the calibration of the rainfall-runoff model. Forecasted rainfall scenarios from downscaled global-oscillation models may be used in the model to evaluate storm runoff and groundwater recharge within the Kawela watershed. The water budget will be compared with a daily water-balance model being developed as part of an island-wide groundwater-availability study by the USGS Pacific Island Water Science Center.

Preliminary Findings

Progress to date includes the evaluation of a preliminary model and the initial collection of rainfall and other meteorological data.

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Information Transfer Program Introduction

None.

Technology Transfer

Basic Information

Title:	Technology Transfer
Project Number:	2007HI192B
Start Date:	3/1/2007
End Date:	8/31/2008
Funding Source:	104B
Congressional District:	Hawaii 1st
Research Category:	Not Applicable
Focus Category:	Education, Water Use, Water Supply
Descriptors:	Technology transfer, Information dissemination
Principal Investigators:	Philip Moravcik

Publication

1. Moravcik, Philip. 2008 (July). Bulletin, University of Hawai‘i at Mānoa Water Resources Research Center, 8 pp.

Introduction

Hawai‘i, as one of the nation’s less populated states, generates many opportunities for water researchers to directly interact with senior administrators and policy makers. In hopes of broadening the knowledge of and appreciation for Hawai‘i’s water resources, WRRC's Technology Transfer Program produces newsletters; arranges and advertises seminars, workshops, and conferences; assists in producing posters and other materials for presentations; and maintains the WRRC website.

Problem and Research Objectives

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

Methodology

WRRC *Bulletin*s; other publications; WRRC website; workshops, meetings, and conferences; and regular biweekly seminars all served to aid the center in transferring to its multiple audiences timely and critical information concerning water-resource research and issues.

Principal Findings and Significance

N/A

Synopsis of activities during the no-cost extension of project 2007HI192B (FY 2007 Technology Transfer grant) for the University of Hawai‘i at Mānoa Water Resources Research Center (WRRC).

In addition to supporting the regular activities or the Technology Transfer Program as outlined in the FY 2008 Annual Technical Report, Technology Transfer Program funds carried over from the FY 2007 grant were used in the development and planning of WRRC's October 2008 Water Quality Conference: "How Clean or Polluted are Hawai‘i's Drinking and Recreational Waters?" The organization of this conference included the involvement of a planning committee which met several times in the first half of FY 2008.

Approximately 125 participants from various regulatory agencies, water utilities, and academia attended the conference. It provided an opportunity for productive communication on some the most critical current water issues being faced by Hawai‘i—including new microbiological and statistical tests for determining sewage contamination of recreational waters and the problems experienced and solutions identified when surface water is added into a groundwater distribution system.

In addition the conference provided a venue for WRRC's Outfall Biomonitoring Team to present an update on the results of the ongoing marine-life monitoring programs they have conducted for more than twenty years at Honolulu's deep-water treated-effluent outfalls. This is a particularly timely subject in Honolulu as the EPA has recently declined to continue granting waivers from secondary treatment to the two largest wastewater treatment plants operated by the City and County of Honolulu which discharge through two of the monitored outfalls.

WRRC sent several conference announcements to a large group of potential attendees. Printing and mailing—including paper and ink, postage costs, and support-staff time—of conference announcements to WRRC's 800+ mailing list consumed much of the balance of the 2007 carryover funds.

Publications Cited in the Synopsis

N/A

Technology Transfer

Basic Information

Title:	Technology Transfer
Project Number:	2008HI234B
Start Date:	3/1/2008
End Date:	8/31/2009
Funding Source:	104B
Congressional District:	Hawaii 1st
Research Category:	Not Applicable
Focus Category:	Education, Water Use, Water Supply
Descriptors:	Technology transfer, Outreach, Information dissemination
Principal Investigators:	Philip Moravcik

Publication

1. Moravcik, Philip. 2008 (February). Bulletin, University of Hawai‘i at Mānoa Water Resources Research Center, 8 pp.
2. Moravcik, Philip. 2008 (July). Bulletin, University of Hawai‘i at Mānoa Water Resources Research Center, 8 pp.
3. Moravcik, Philip. 2008 (December). Bulletin, University of Hawai‘i at Mānoa Water Resources Research Center, 8 pp.

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During this reporting period WRRC organized a two-day conference bringing together local stakeholders and decision makers with both local and out-of-state water researchers to discuss the issue of how polluted the recreational and drinking waters of Hawai‘i really are—a matter of ongoing debate in the local media.

This year also marked the initiation of the center's program to make the WRRC archive of over four hundred WRRC-generated research reports available over the internet as full-text documents.

Problem and Research Objectives

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

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Principal Findings and Significance

N/A

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 Principal Investigator

(PI) also participated in school science fairs, WRRC research projects having an informational component, and refinement of the WRRC web site.

During this current reporting period the Technology Transfer Program produced three newsletters describing research projects and center activities and news. During this reporting period the Technology Transfer Program PI 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 seminar series 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 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 seventeen seminars presented during the reporting period.

Spring 2008—Coordinator Dr. James Moncur

2/7/08 Dr. Victor Moreland, WRRC Researcher, University of Hawai‘i

White Paper Recommending Approval of the City and County of Honolulu's Honouliuli Wastewater Treatment Plant's Application for a Modified NPDES Permit under Section 301(h) of the Clean Water Act

3/19/08 Drs. James Roumasset, WRRC Researcher/Dept. of Economics, University of Hawai‘i, and Kimberly Burnett, University of Puget Sound, Economics, and University of Hawai‘i Economic Research Organization

Sustainable Yield to Sustainable Development to Sustainable Science: History of Thought and Research Challenges

4/11/08 Don Thomas, Director, Center for the Study of Active Volcanoes, University of Hawai‘i

Stratigraphy and Hydrologic Conditions in the HSDP II Borehole: Implications for Ocean Island Stability

4/14/08 Drs. H.D.Taylor and J.E.Ebdon, University of Brighton, School of the Environment and Technology

The Origin of Feces: Development and Implementation of Novel Microbial Source Tracking (MST) Techniques in Europe and Beyond

5/8/08 Michael Cooney, Associate Researcher, Hawaiʻi Natural Energy Institute, University of Hawaiʻi

Water Use in the Production of Bio-Fuels

5/15/08 R.W. Gentry, Ph.D., P.E., Director, Institute for a Secure and Sustainable Environment, The University of Tennessee

The New Paradigm of Sustainability Science and its Application to Natural Systems

Fall 2008—Coordinator Dr. Roger Babcock

9/4/08 Dr. David Callies, Professor of Law, William S. Richardson School of Law, University of Hawaiʻi

Why Water Use Should Not Trump Planning, and the Perversion of Public Trust

9/18/08 Dr. Aly Fares, Associate Professor, Watershed Hydrology and Tropical Soils, College of Tropical Agriculture and Human Resources, University of Hawaiʻi

Coastal Watershed Management: Book Overview

10/9/08 Dr. Jose Salas, Department of Civil & Environmental Engineering, Colorado State University, Fort Collins, Colorado

Use of Tree Ring Indices for Reconstructing Streamflows with Applications on Drought Analysis

10/16/08 Drs. Aly El-Kadi, Professor, Department of Geology and Geophysics, University of Hawaiʻi, and Roger Fujioka, WRRC, University of Hawaiʻi

Restoration and Protection Plan for Nawiliwili Watershed, Kauaʻi

11/3/08 Len Materman, Center on Ecotourism and Sustainable Development, Stanford University

Special Seminar—From Waves to Watersheds: Integrating Socio-Economic and Environmental Values to Build Sustainability

11/20/08 Dr. Greg Bruland, Assistant Professor, Natural Resources and Environmental Management, College of Tropical Agriculture and Human Resources, University of Hawai‘i

Coastal Wetlands

12/4/08 Drs. James Roumasset, WRRC Researcher/Dept. of Economics, University of Hawai‘i, and Kimberly Burnett, University of Hawai‘i Economic Research Organization

Sustainability Science for Watershed Management

Spring 2009—Coordinator Dr. Aly El-Kadi

1/15/09 William Cutler, Integral Consulting, Inc., and Graduate Research Assistant, Department of Geology and Geophysics, University of Hawai‘i

Managing Arsenic-Contaminated Land in Hawai‘i

2/5/09 Amjad Ahmad, Graduate Research Assistant, Department of Natural Resources and Environmental Management, University of Hawai‘i

Impact of Different Organic Amendments on the Water Quantity and Quality of the Vadose Zone Hydrology in a Hawaiian Watershed

2/19/09 Robert Whittier, The Environmental Company, and Graduate Research Assistant, Department of Geology and Geophysics, University of Hawai‘i

Environmental Risk Ranking of On-Site Disposal Systems

2/26/09 Dr. Susan Taylor, ERDC-Cold Regions Research and Engineering Laboratory

Dissolution Rate and Weathering Mechanics of TNT, Comp B, Tritonal, and Octol

Water Quality Conference: 30–31 October 2008

In October 2008 the Technology Transfer Program organized a water-quality conference on "How Clean or Polluted are Hawai‘i's Drinking and Recreational Waters?" The underlying premise of this conference was that the best way to determine if water is polluted is to rely on water-quality monitoring data. Thus, the conference goals were stated as follows:

1. To focus on the use of water-quality monitoring data as the basis for determining the degree of pollution and relative safety of recreational and drinking water in Hawai‘i.

2. To initially review the adequacy of routine monitoring data for recreational waters to meet the Clean Water Act/Beach Act and for drinking waters to meet the Safe Drinking Water Act.

3. To assess the degree of pollution and health risk posed by these same water sources based on routine quality-monitoring data as well as other monitoring data and applying the "weight of evidence" approach.

4. To identify needs in developing methods capable of more rapidly and reliably measuring a larger variety of pollutants and providing more reliable risk assessments for human and environmental health than current methodologies.

5. To provide recommendations for future actions.

Speakers invited to present at this conference included: Dr. Nicholas Ashbolt (Title 42 Senior Research Microbiologist with the National Exposure Research Laboratory, U.S. EPA, Cincinnati) and Dr. Richard Whitman (Chief of the USGS Lake Michigan Ecological Research Station).

The conference was attended by more than 120 academics, consultants, environmental activists, and leaders of Hawai'i's water management agencies and water and wastewater utilities.

WRRC Website

The Technology Transfer Program continually updates the center's website (www.wrrc.hawaii.edu) with new information about WRRC researchers' activities, seminars, reports, meetings, grant announcements, and the center's L. Stephen Lau scholarship fund. The website provides information about center facilities and personnel as well as a database of WRRC publications. A website search function provides easy access to the available information.

Digitization and Online Posting of WRRC Publications

In collaboration with the University of Hawai'i at Mānoa's ScholarSpace institutional repository program, the Technology Transfer Program initiated the digitization of WRRC's archive of reports generated by the many WRRC projects conducted over the past forty years. Digitized reports are available for downloading in PDF format at the ScholarSpace website (http://scholarspace.manoa.hawaii.edu/).

Previously, individuals wanting to access these reports would have had to write to WRRC and request, for a fee, to have a copy mailed to them. This initiative represents a substantial milestone in our efforts to disseminate the results of WRRC research.

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. Two graduate-research-assistant posters were recognized by conference awards.

Publications Cited in the Synopsis

N/A

USGS Summer Intern Program

None.

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	3	0	0	0	3
Masters	5	1	0	0	6
Ph.D.	7	6	0	1	14
Post-Doc.	0	0	0	1	1
Total	15	7	0	2	24

Notable Awards and Achievements

Project 2008HI231B (PI: Dr. Weilin Qu) has received follow-on funding. The solar-energy-driven HDH seawater desalination research program recently received $48,000 in funding from Hawaii Technology Development Venture (HTDV) to support a project entitled “Solar Energy Driven Humidification-Dehumidification Seawater Desalination Systems.” Dr. Qu's research team will collaborate with a local technology company to design, construct, and test a laboratory-scale prototype HDH desalination system.

Publications from Prior Years