Water Resources Research Center
Annual Technical Report
FY 2003

Introduction

In the 2003-04 report period, the University of Hawaii Water Resources Research Center continued with its principal focus on water quality issues including water recycling, operation of wastewater treatment facilities, wind-powered desalination systems, runoff/recharge processes and economic models of water allocation, pricing and efficient use.

WRRC added one faculty member during this period, Dr. T. Kaeo Duarte, bringing the faculty up to 6.5 FTE and 10 persons, in addition to clerical, publications and laboratory staff of seven. The joint appointments cover engineering, economics, geology, ecology and oceanography. Faculty from several other units of the university participate as principal investigators.

Some 27 projects were active at some point in the report period. Aside from the USGS grant that gave rise to this report, support came from the University of Hawaii (for salaries and space), the U.S. Environmental Protection Agency, U.S. Departments of the Army and Navy, the Hawaii State Departments of Health and Agriculture, the City Department of Environmental Services and several private sector organizations.

Research Program

The USGS/WRRIP grant for fiscal 2004 allowed the funding of three research projects, in addition to technology transfer and administrative activities. One (Prevention of Colloidal Fouling...) is closer to basic than applied research in nature, and should provide the basis for development grants. A second (...Transport of Pharmaceutical Compounds and Pathogens...) investigates for Hawaii soil conditions a problem only recently recognized nationally. The third (A Win-Win Approach...) simulates the conservation effects of efficient water pricing, with rates adapted to different elevations and with minimum quantities provided at low cost.

In addition, three earlier WRRIP-funded projects remained active to complete work begun the previous year, and work on a supplemental grant was concluded.

Prevention of Colloidal Fouling in Crossflow Membrane Filtration: Searching for Optimal Operation Conditions

Basic Information

Title:	Prevention of Colloidal Fouling in Crossflow Membrane Filtration: Searching for Optimal Operation Conditions
Project Number:	2003HI26B
Start Date:	3/1/2003
End Date:	2/28/2005
Funding Source:	104B
Congressional District:	Hawaii 1st
Research Category:	Water Quality
Focus Category:	Treatment, Solute Transport, Models
Descriptors:	
Principal Investigators:	Albert Sechurl Kim, Clark C.K. Liu

Publication

1. Kim, A.S.; R. Yuan, Specific cake resistance due to filtered aggregates: Creeping flow relative to a swarm of solid spheres with a porous shell, Membrane Science, submitted.

Problems and Research Objectives

Colloidal fouling in crossflow membrane filtrations

Crossflow membrane filtration processes involving reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), and microfiltration (MF) have steadily gained importance in environmental engineering separations over the past decade. Numerous improvements in the technology—for instance, development of highly selective and permeable membranes, and efficient module designs—and several improvements in peripheral technology have spurred widespread adaptation of these processes in environmental, chemical, pharmaceutical, and biomedical applications. MF and UF, in particular, are widely used to remove suspended solids, colloidal particles, macromolecules, bacteria, and viruses from feed solutions, with particular applications as alternative, substitutional, or supplementary processes for conventional water and wastewater treatment. The major limiting factor of MF/UF applications is the ratio of permeate flux (with appropriate water quality) to invested cost since membrane fouling often increases the maintenance cost. While filtering particulate matter, MF/UF membranes undergo three different patterns of matter-stacking phenomena on their surfaces: (1) concentration polarization, (2) (followed by) colloidal cake/gel formation, (3) and aggregate cake formation (i.e., cake of retained aggregates composed of many small primary colloidal particles). All three fouling patterns constrict the permeation rate, and each effect brings out its own permeate flux decline behavior.

The most typical fouling pattern that occurs during MF/UF filtration is colloidal cake formation. A generated cake layer contributes additional hydraulic resistance and thereby reduces the permeate flux. One of the most important governing factors of this type of fouling is cake porosity, which is mainly affected by transmembrane pressure, membrane resistance, solvent (typically water) viscosity, ionic strength, pH, zeta potential, temperature, and particle size. The complexity of the many physical, chemical, and operational parameters often makes it difficult to decide on practical operational conditions for higher flux at (possibly simultaneously) less cost. Therefore, one objective of this research is to determine optimal operational conditions by changing a few controllable parameters among those listed above in the presence of the colloidal cake layer. A second objective is to conduct a theoretical investigation of the aggregate cake layer, another type of cake layer that can contribute to membrane fouling, albeit in a different way. In feed water of high ionic strength, aggregates that form in the bulk phase are deposited on the membrane surface. Due to the high porosity (up to 0.99) of the aggregates, this cake layer causes remarkably less flux decline than the colloidal cake layer. Practical utilization of this phenomenon can reduce the operating cost, especially in MF/UF filtration processes as pretreatment of RO/NF.

Relevance and importance to Hawaii

Desalination processes to produce portable water from seawater or brackish water have become increasingly important due to the paucity of freshwater, especially in the state of Hawaii. Water desalination can be accomplished by using either thermal (distillation) or membrane technology. Because of the advancement of membrane technology, most water desalination plants built in the last thirty years have mainly used RO, electrodialysis (ED), and NF. Nevertheless, the use of RO/NF membranes in water treatment processes is hindered by the presence of particulate foulants such as dissolved natural organic matter, small colloids composed of natural silica, clays, organics or biological matter, and ionic constituents, which must be removed in pretreatments of MF/UF. Therefore, this research will enhance our understanding of fouling problems in desalination processes and thus will help in the development of solutions to prevent potential fouling phenomena.

Methodology

Computer simulations for formation of colloidal cake layer

Any theoretical approach cannot predict the realistic structure of the colloidal cake layer or its resulting porosity, especially in a concentrated particulate system. To overcome this limitation, a brute force simulation scheme was selected for this research project. The PI had used a statistical simulation method called NPT Monte Carlo (MC) simulation to investigate the colloidal cake structure. Here, NPT indicates that constant during the simulation are number of particles N, pressure P, and temperature T.

Although the NPT MC method well described the cake structure with given physical and chemical conditions (e.g., pH, ionic strength, Hamaker constant, applied pressure, and temperature), it was limited to a vanishing flux situation, in which membrane resistance is highly negligible compared to cake resistance. As a result, the NPT MC scheme somehow overestimates porosity of the colloidal cake layer since the hydrodynamic permeation-drag exerted on each particle on the membrane surface was not systematically considered. Therefore, the Mean Field Hydrodynamic Force Bias Monte Carlo (MFHFB-MC) scheme is introduced in this research project to investigate how much more the colloidal cake layer can be compressed due to the permeate flow. FORTRAN codes were recently developed and partially tested, and the outcomes were reasonable. A complete set of simulations will start in June 2004, and analysis of the results will follow.

Theory for specific resistance of aggregate cake layer

Specific cake resistance due to a number of aggregates deposited on the membrane surface is investigated. Each deposited aggregate is considered a collection of many primary fine colloidal particles so that a continuum-level approach is applied. The internal structure of an aggregate is treated as a solid core with a uniformly porous permeable shell, and the effect of neighboring aggregates is included by employing an outer tangential-stress-free surface. The mathematical solution of this model is successfully providing the specific cake resistance of the aggregate cake layer. In addition to this model of the composite sphere is the development of the specific cake resistance of aggregates, of which hydraulic permeability is quadratically increasing with respect to distance from the center of the mass of aggregates.

Principal Findings and Significance

Computer simulations for formation of colloidal cake layer

A few runs of the MFHFB-MC simulation provided the following scientific findings. (1) Cake structure represented as the porosity is independently governed by both applied pressure and intrinsic membrane resistance, even if during filtration the membrane resistance is negligible compared to the colloidal cake resistance. The reason is why particles are experiencing fluid velocity that is the same as the initial flux which is proportional to ratio of the applied pressure to the membrane resistance. (2) As expected, incorporating hydrodynamic drag exerted on each particle in the colloidal cake layer reduces the cake porosity, and the corresponding flux decline follows since the drag effectively compresses the cake configuration down to the membrane surface.

Theory for specific resistance of aggregate cake layer

An aggregate typically characterized by a dense center and sparse edge can be modeled by a composite sphere of a solid core with a porous shell. With this transformation, the hydrodynamic drag force exerted on each aggregate can be easily estimated, Further, the specific resistance of the aggregate cake can be predicted with three measurable parameters: (1) occupancy ratio of aggregates within aggregate cake layer, (2) size of the solid core, and (3) permeability of the uniform porous shell.

Publications and presentations

One paper and two conference presentations report on the research. The paper was submitted to *Membrane Science* and is being revised based on a favorable review. The conference presentations are listed below.

Kim, A.S.; R. Yuan, 2003, Creeping flow relative to a swarm of fractal aggregates, paper presented at the annual meeting of the American Institute of Chemical Engineers, San Francisco, California.

Kim, A.S.; R. Yuan, 2004, Hydraulic resistance due to aggregate cake in microfiltration/ultrafiltration membrane processes, paper presented at the annual Hawaii section conference of the American Water Works Association, Honolulu, Hawaii.

An Evaluation of Factors Affecting the Transport of Pharmaceutical Compounds and Pathogens in Selected Hawaii Soils for Land Application of Wastewater

Basic Information

Title:	An Evaluation of Factors Affecting the Transport of Pharmaceutical Compounds and Pathogens in Selected Hawaii Soils for Land Application of Wastewater
Project Number:	2003HI27B
Start Date:	3/1/2003
End Date:	2/29/2005
Funding Source:	104B
Congressional District:	Hawaii 1st
Research Category:	Water Quality
Focus Category:	Water Quality, Groundwater, Waste Water
Descriptors:	
Principal Investigators:	Chittaranjan Ray, Albert Sechurl Kim

Publication

Problem and Research Objectives

Mobility of virus, bacteria, and pharmaceuticals and personal care products (PPCPs) in subsurface media and their arrival in groundwater has significance for public health. Pathogens are sources of disease, whereas PPCPs, which are chemicals that can affect the endocrine system of animals and humans, can be mutagenic and carcinogenic. The sources of human and animal pathogens that may impact groundwater quality are land-applied sludge, manure, and wastewater; storage sites for manure; cesspools and septic tanks; leaky sewers; lagoons for the storage of human and animal wastes; barnyards; and feral animals. Wastewater and manure are also typical sources of PPCPs. Land is generally used for the disposal of human and animal wastewater, manure, sludge, and other substances. Land application of wastewater is practiced in many areas of the world where increased water shortage has necessitated the need for irrigation of croplands and the recharge of aquifers with treated wastewater. Also, restrictions on the disposal of wastewater in waterways and oceans forced the municipalities to consider land disposal as an alternate method. In many areas of the United States, state and local governments have passed regulations mandating incremental reuse of wastewater over a given timeframe. In the context of soil-aquifer treatment for the recharge of aquifers with treated wastewater or surface water, the pumping centers in potable aquifers are some distance away from land application areas. Also, in the arid southwestern part of the continental United States where land application is heavily practiced, the depths to potable water supply aquifers are deep and the municipal wellfields are at significant distances from effluent use areas. However, increased regulations on enhanced reuse have necessitated the application of wastewater directly over drinking water aquifers in parts of the country, such as in Hawaii. Similarly, leaky sewers, manure pits, animal effluent lagoons, and farms lands that receive manure or sludge can be found in areas overlying shallow aquifers.

Generally, it is believed that the physical and chemical characteristics of the soil and to some extent the characteristics of the pathogens (as well as the PPCPs) affect their transport in subsurface media. If a soil is aggregated, it provides preferential pathways for pathogen- or PPCP-containing water to pass through the topsoil. Fractures and cracks in subsoil accelerate the movement of this water. The clay and organic matter content of the soil affect the sorption of pathogens and PPCPs, while soil pH and the isoelectric point of the pathogens affect their attachment. Also, it is believed that the mineral oxides provide positively charged sites to retain these pathogens in the soil. The degree of saturation of the subsoil media may have some effect on the mobility of pathogens. If the water content is reduced, it is hypothesized that the travel path will be longer. Also, a smaller thickness of the water film around the particles allows greater attachment potential of the pathogens to the particles.

An initial evaluation of a local soil (a tropical Oxisol) showed that it has high potential for retaining a large number of bacteria and viruses in the top three inches of packed soil columns. Oxisol contains a large percentage of clay-size particles and is high in oxides, iron, and manganese. For this soil, batch-equilibrium sorption experiments conducted for bacteriophage showed a high sorption distribution coefficient. As for bacterial sorption, although methodological problems caused some difficulties in quantitation, the initial results showed higher retention. Although this result has aroused widespread interest locally on the reuse of effluent on land directly overlying potable water aquifers, we strongly believe that additional laboratory and field evaluations are essential prior to large-scale land application efforts. More remains to be done in characterizing various soils in terms of their physical and chemical properties where land application of wastewater is being or is planned to be practiced. Most soils in temperate climates have fixed charges, whereas many soils in the tropics exhibit variable charges. In addition, quantification of attachment and detachment of the bacteria and viruses through batch equilibration sorption tests or through flow-through column experiments needs to be evaluated.

The overall goal of this research is to evaluate the impact of soil physical and chemical parameters that affect the transport of pathogens and PPCPs, especially under Hawaii conditions. The key questions that will be answered through this research over a two-year funding cycle are:

1. How would the bacteria, viruses, and selected PPCPs move in a variety of soils collected from several places in Hawaii?
2. What are the key soil physical and chemical parameters affecting pathogen and PPCPs transport?
3. Can these parameters be manipulated by amendments or by the physical setting of the site to affect pathogen and PPCP transport?
4. Can existing models be used to quantify pathogen and PPCP transport in the subsurface?

Methodology

In order to answer the above outlined questions, the following tasks are being undertaken. Since the project scope is wide and the work is expected to last two years or more, we plan to address the transport of PPCPs in soil columns in the first year and to conduct transport studies of bacteria and viruses in soil columns in the second year. After that, laboratory experiments will be conducted to manipulate soil characteristics in order to observe the impact on transport. Modeling exercises will be conducted at the conclusion of the study. Although initially planned for two years, we think that the study may last for three years. We are seeking additional sources of funding to conduct various tasks that may not be accommodated with funding for this project.

The questions outlined above will be achieved by undertaking the following tasks in a phased approach.

Task 1. How would the bacteria, viruses, and selected PPCPs move in a variety of soils collected from several places in Hawaii?

Transport studies are being conducted under conditions similar to those reported by T.P. Wong and C. Ray (Proceedings, World Water and Environment Conference, May 20–24, 2001, Orlando, Florida, American Society of Civil Engineers, Reston, Virginia, CD-ROM, 9 pp). Initially, the soils are irradiated with Co^{60} for an appropriate amount of time to kill all pathogens. PPCPs typically found in treated wastewater are used for column transport experiments. Loading rates of the leaching solution are similar to those of Wong and Ray (2001). These rates are higher than the agronomic rates since it is not feasible to get a breakthrough of these chemicals in a reasonable amount of time using agronomic rates. The ionic strength of the leaching solution is adjusted with $CaCl_2$ to make it close to that of rainwater. Following these experiments, microbial experiments are planned. Two viruses, one with a low isoelectric point (e.g., MS-2) and the other with a high isoelectric point (e.g., X174) are considered for this experiment. In addition, the bacteria *Escherichia coli* is the microbe considered.

Task 2. What are the key soil physical and chemical parameters that affect the transport of pathogens and PPCPs?

The collected soils are analyzed for their physical and chemical characteristics to relate their mobility to soil characteristics. First, the soils are analyzed for particle-size distribution. The amount of clay-size particles present in each soil and the pH of the soil solution (1:5 paste) are examined. Second, the amount of organic matter present in each soil, the cation exchange capacity, and the sum of the bases; and total ions of sodium, calcium, magnesium, and phosphate, as well as their exchange concentrations, are analyzed by a contract laboratory. Most important of all, the samples are analyzed for iron and aluminum oxides.

The soils of tropics, including many in Hawaii, show variable charge. This can simply be observed by closely examining a soil survey investigation report (i.e., see Soil Conservation Service, 1976, Soil Survey Invest. Rep. No. 29, Washington, D.C.). For example, the pH of several soil solutions (1 part soil to 5 parts fluid) in KCl at depths of 50 cm can be observed to be higher than that of pure water. The topsoil seems to behave in the opposite way. This report also provides general information on the mineralogical composition and the organic carbon content of the soil. Measurement of permanent charge in a mixed system, a specific surface, and the zero-point charge is planned to be done following the methods of G. Uehara and G. Gillman (*The Mineralogy, Chemistry, and Physics of Tropical Soils with Variable Charge Clays,* 1981, Westview Press, Boulder, Colorado). Our main focus is to relate pathogen retention in columns to the zero-point charge of the soil and the isoelectric points of the pathogens.

Task 3. Can the physical and chemical parameters be manipulated by amendments or by the physical setting of the site to affect pathogen and PPCP transport?

Soil amendments such as gypsum and lime affect the pH of the soil. This could also shift the zero-point charge on clay surfaces. Addition of manure and other organic waste material can affect the transport behavior of chemicals and pathogens. For this purpose, we limit our experiments to the addition of surfactants, polyelectrolytes (e.g., polyacrylamide [PAM]), and natural organic matter to the soils. Planned experiments with linear alkylbenzene sulfonate (LAS) and PAM are similar to those conducted in the preliminary study (Wang and Ray, 2001). Sterilized sewage is a good source of natural organics. Sorption and transport experiments are planned to examine the impact of these additives on pathogen and PPCP mobility. At the end, lime and gypsum can be added to two columns as a pH modifier. The comparative evaluation of the transport of phages and *E. coli* for various soil amendments is to be done using the pH conditions, zero-point charge of the soil, pH of the amendments, and the isoelectric point of the phage or bacteria. The same comparison is to be made for PPCPs in PAM/LAS-treated and untreated soils.

Task 4. Can existing models be used to quantify pathogen and PPCP transport in the subsurface?

Data from batch and column experiments can be used to estimate sorption parameters for modeling. Estimation of sorption parameters from batch equilibration tests for predicting transport in column experiments has limited use. Apparent equilibration is normally assumed in batch studies, whereas kinetic attachment and detachment are needed to describe transport in columns. However, one difficulty arises if no breakthrough from the column is obtained in a reasonable amount of time for the pathogens. In that case, eluted concentrations from given depths at the end of the experiment can be used to examine transport behavior. The attachment rate coefficients of bacteria and viruses are normally related to the collision efficiency and the single-collector efficiency. Theoretically predicted parameters can be compared against actual data. Breakthrough data for PPCP from soil columns can provide needed transport parameters for simulation.

Principal Findings and Significance

Two soil types—an Oxisol and a Mollisol—were collected and air dried. The air-dried soil samples were irradiated with Co^{60} and stored in the refrigerator until use. Flow cells were built to hold the soil at field-measured bulk densities. Leaching experiments are being conducted using high performance liquid chromatography (HPLC) pumps, fraction collectors, and a vacuum chamber under unsaturated conditions. Bromide and a fluorescent tracer were initially used for obtaining transport parameters for the column. However, because the background fluorescence was sufficiently high to cause interference with the fluorometer, only the bromide breakthrough data are being used.

We are also developing methods for analyzing several dozen PPCPs in a non-WRRIP project. We found that the wastewater from one of the treatment plants on Oahu contains compounds such as atrazine, lindane, 17-ß estradiol, estrone, NDMA, octylphenol, and nonylphenol. We have resolved and refined analytical methods for all compounds except NDMA. Experiments with these compounds in packed columns of the two soils will be conducted in the next few months. Then we will characterize the soils for their pH-dependent charge.

We plan to conduct microbial transport experiments in FY 2004. We will also amend the soils in these columns by adding lime or other materials. Modeling work will be conducted at the conclusion of these experiments.

A Win-Win Approach to Water Pricing and Watershed Conservation

Basic Information

Title:	A Win-Win Approach to Water Pricing and Watershed Conservation
Project Number:	2002HI2B
Start Date:	3/1/2002
End Date:	2/28/2005
Funding Source:	104B
Congressional District:	Hawaii 1st
Research Category:	Social Sciences
Focus Category:	Economics, Conservation, Water Supply
Descriptors:	economics, allocation, pricing, conservation
Principal Investigators:	James A. Roumasset, Rodney B.W. Smith

Publication

1. Kaiser, B.; W. Matsathit; B. Pitafi; J. Roumasset, 2003, Efficient Water Allocation with Win-Win Conservation Surcharges: The Case of the Koolau Watershed, Working Paper, Water Resources Research Center, University of Hawaii at Manoa, Honolulu, Hawaii.
2. Pitafi, B.; J. Roumasset, 2003, Efficient Groundwater Pricing and Intergenerational Welfare: The Honolulu Case, Working Paper, Water Resources Research Center, University of Hawaii at Manoa, Honolulu, Hawaii.

Problem and Research Objectives

Several studies have documented that inter-temporal water allocation in Hawaii is inefficient. However, the consequences of misallocation, including the economic value lost, are unknown. In addition, proposals for efficiency pricing have often been found to be politically infeasible because current users will have to pay a higher price even though future users will be better off. Moreover, other sources of mismanagement, including spatial misallocation and under-maintenance of watersheds, need to be considered in an integrated framework in order to assess the nature and size of the problem and the potential gains from policy reforms.

The overall objective of the project is to combine existing hydrological, engineering, and economic knowledge in order to estimate efficient water use on Oahu. Pricing schemes for achieving efficient use are calculated. We show how efficiency pricing can be rendered politically feasible by compensating the users suffering a loss due to higher prices. Finally, rather than take aquifer recharge rates as exogenous to water management, we incorporate watershed management as one of the policy instruments.

Methodology

We estimate optimal groundwater usage with and without the watershed conservation plan. The modeling framework constructed estimates optimal groundwater extraction quantities while avoiding over-extraction that would lead to salinity in existing wells and using desalted water as supplemental source as warranted by demand. A hypothetical social planner chooses the extraction rate of water from the aquifer to maximize the present value of net social surplus. The dynamic of the head level is governed by the amount of water inflow, leakage, and extraction rate. We allow different discount rates, demand growth rates, usage at different elevations with different distribution costs, and different changes in forest recharge levels. The effects of watershed conservation are introduced in the form of probabilistic changes in recharge.

Principal Findings and Significance

We have constructed modeling frameworks, estimated parameters for each aquifer, and conducted simulations for the cases of Pearl Harbor and Honolulu aquifers. These studies pioneer a methodology for integrating economic, hydrological, engineering, ecological, and political considerations in the determination of optimal water management.

The Pearl Harbor Case

We investigate the economic benefits of conserving a forested watershed in conjunction with efficiency pricing of the downstream groundwater resource. We find that under a wide range of parameter assumptions, investment in watershed conservation will generate positive benefit-cost ratios, even before accounting for biodiversity and other conservation benefits.

We examine the value of conservation of a forested watershed, assuming that watershed degradation occurs with low probability (between 1% and 20%). We start by describing the impacts of a certain loss of forest quality and associated recharge. If 31% of the recharge from the Koolau mountain watershed area on Oahu is lost, this will decrease recharge to the Pearl Harbor aquifer by 15% and decrease the present value of the aquifer by more than $1.2 billion, assuming a 3% social discount rate and efficient resource use.

We then adapt the methodology used to determine this definitive loss in order to calculate the expected loss in social welfare from an uncertain probability of forest quality degradation. Assuming a modest probability of 10% that the resource is degraded, reducing aquifer recharge 15% after 20 years, we find that the expected benefits of conservation are $89 million using a 3% discount rate. This figure is robust to a large number of parameter changes. This estimate assumes that the resource manager optimally solves the problem of water extraction under uncertainty and knows that the optimal price path is discontinuous and jumps up or down after the event or non-event is realized. In the likely event of mismanagement, inasmuch as water managers are typically unfamiliar with economic optimization even under certainty, the gains of conservation will be larger.

Policymakers have indicated that the costs of successful conservation may be as high as $15 million. Even at such high costs, conservation combined with efficient water management is a win-win-win solution for consumers, taxpayers, and the environment, albeit in the sense that the environmental insurance acquired through conservation costs less than its expected value. Only in cases where the probability of the event is very low (1%) do the estimates of expected social loss fall below $15 million. Even a 1% chance of a 5% loss at a 1% discount rate generates $17 million in lost welfare.

The Honolulu Case

We analyze two scenarios of water usage/pricing. (a) *Status-quo pricing* — We derive the extraction rates dictated by demand resulting from continuation of the current pricing (equal to cost) and estimate the resulting welfare. (b) *Efficiency pricing* — This is a scenario in which insufficient conservation efforts causes the risk of reduced recharge.

We find that if the status-quo policy of pricing water at average (extraction and distribution) cost is continued, consumption will grow quickly and the groundwater aquifer will be depleted fast (in about 57 years), with the head level reaching the minimum allowable (to avoid salinity). After that, extraction of groundwater cannot exceed the recharge rate. Any excess demand at that time and any future growth in demand must be met using the more-expensive desalination technology. Status-quo pricing does not differentiate users by distribution costs and results in subsidies from lower-elevation users (with lower distribution costs) to higher-elevation users. Efficiency pricing requires a slight price increase in the first year. This price rises smoothly over time, but faster than the status-quo price, until the aquifer reaches the minimum allowable head level and desalination has to be used (in year 76). Because the efficiency price includes category-specific distribution cost, it avoids distribution-cost subsidies from lower- to higher-elevation users.

The efficiency-pricing regime is compared to status-quo pricing in terms of welfare. Since the efficiency prices are higher than the status-quo prices, initially users lose welfare by switching from status-quo to efficiency pricing. This is not true for users in the lowest-elevation category who actually gain welfare because they do not have to subsidize the distribution cost of the higher-elevation users. Since most of the consumption occurs at the lowest elevation, these gains are substantial. Over time, however, as the efficiency prices rise, all categories see increasing losses relative to status-quo pricing (the present value of all losses is estimated at $34 million). Later, efficiency pricing becomes welfare-superior to status-quo pricing and remains superior afterwards because the status-quo policy would require the use of expensive desalination technology sooner and would rely on it more heavily than efficiency pricing. Thus efficiency pricing provides greater welfare to users in all elevation categories later on (the present value of the gains is estimated at $441 million).

Switching to efficiency pricing causes some (mostly high-elevation and near-term) users to lose welfare and some (mostly low-elevation and future) users to gain. The resulting political problems can be avoided by actually compensating the losers. This is achieved by proposing a compensation system for welfare-losing users through a free block. The deficit resulting from the compensation scheme (to losers in the near future) is financed by debt, which is repaid out of the gains to future consumers. Efficiency pricing is thus made actually Pareto-improving by compensating those who lose welfare due to the switch from status-quo pricing.

Confirming the Natural Presence of Fecal Indicator Bacteria in Environmental Soil and Water on the Islands of Kauai and Hawaii

Basic Information

Title:	Confirming the Natural Presence of Fecal Indicator Bacteria in Environmental Soil and Water on the Islands of Kauai and Hawaii
Project Number:	2001HI2082B
Start Date:	3/1/2001
End Date:	2/28/2004
Funding Source:	104B
Congressional District:	First
Research Category:	Water Quality
Focus Category:	Water Quality, Non Point Pollution, Water Use
Descriptors:	health effects, tropical environment, water quality standards, fecal indicator bacteria
Principal Investigators:	Roger S. Fujioka

Publication

1. Vithanage, G, 2002, Assessment of sewage pollution in Hawaii's stream based on concentrations of FRNA coliphages, poster presented at 24th annual Hawaii Water Environment Association conference, Hawaii Convention Center, Honolulu, Hawaii.
2. Vithanage, G.; G. Ueunten; E. Akazawa; R. Fujioka, 2003, Need for alternative fecal indicators (C. perfringens, coliphages) to assess hygienic quality of streams and beaches on Kauai, Hawaii, abstract of poster presented at 103rd general meeting of the American Society for Microbiology, Washington, D.C., p. 590.
3. Fujioka, R.; K. Luther; G. Vithanage, 2004, Assessment of FRNA coliphages in tropical streams: Sewered versus non-sewered area, invited talk presented at the International Workshop on Coliphages as Indicators of Fecal Contamination in Water and Other Environmental Media, Crowne Plaza Hotel, Arlington, Virginia, sponsored by United States Environmental Protection Agency, Office of Water.

Problem and Research Objectives

Our laboratory at the Water Resources Research Center, University of Hawaii, has been conducting water quality studies in the state of Hawaii for the past 30 years. One of the most significant results of these studies is our conclusion that U.S. Environmental Protection Agency (EPA) hygienic recreational water quality standards are not applicable to the state of Hawaii (R.S. Fujioka et al., 1988, *Toxicity Assessment* 3:613–630; R.S. Fujioka and M.N. Byappanahalli, 1996, WRRC-96-01, Proj. Compl. Rep., 50 pp.). This conclusion is based on years of monitoring data which show that all streams on the island of Oahu consistently exceed the EPA hygienic recreational water quality standards based on concentrations of fecal indicator bacteria (i.e., fecal coliform, *Escherichia coli*, and enterococci) (R.S. Fujioka et al., 1988, *Toxicity Assessment* 3:613–630; C.M. Hardina and R.S. Fujioka, 1991, *Environ. Toxicol. Water Qual.* 6:185–195). This conclusion is also based on our assessment that the two assumptions used by EPA to interpret the public health risks of recreational water quality standards are not applicable to Hawaii. The reason is because environmental conditions in Hawaii differ from environmental conditions in temperate regions of the world where monitoring data were obtained for use in establishing recreational water quality standards.

The first assumption used by EPA is that there are no significant environmental sources of fecal indicator bacteria. Thus, EPA assumes that the source of fecal indicator bacteria in natural environmental waters is sewage or animal feces. Moreover, when the numbers of these fecal indicator bacteria exceed their respective maximum contaminant levels, under EPA guidelines these waters are considered polluted with sewage and the sewage-borne pathogens will pose an unacceptable risk to users of those waters. However, based on our studies, we have determined that soil in Hawaii is a natural habitat for fecal indicator bacteria. Moreover, rain, which is the source of water for all streams, will transport these soil-bound fecal indicator bacteria to all streams (C.M. Hardina and R.S. Fujioka, 1991, *Environ. Toxicol. Water Qual.* 6:185–195). Thus, soil rather than sewage or feces of animals is the major source of fecal indicator bacteria recovered from all streams of Oahu.

The second assumption used by EPA is that fecal indicator bacteria cannot multiply under natural environmental conditions. However, the results of our studies have shown that environmental conditions (temperature, moisture, nutrients) in Hawaii's soil environment allow these bacteria to multiply (R.S. Fujioka and M.N. Byappanahalli, 1998, WRRC-98-04, Proj. Compl. Rep., 85 pp.; M.N. Byappanahalli and R.S. Fujioka, 1998, *Water Sci. Tech.* 38:171–174). This second assumption is of critical importance because many significant sewage-borne pathogens such as human enteric viruses and protozoa (*Giardia*, *Cryptosporidium*) are not able to multiply under environmental conditions. As a result, if fecal indicator bacteria multiply in the environment, their numbers no longer represent the degree of sewage or fecal contamination and no longer represent the same risk for water-borne transmission of sewage-borne pathogens.

Since the two assumptions used by EPA to establish and interpret hygienic water quality standards are not applicable to Hawaii, we concluded that the recreational water quality standards also are not applicable to Hawaii. An important consequence of applying the EPA recreational water quality standards to Hawaii is that all streams will consistently exceed the hygienic water quality standards. Although we have obtained data to show that the source of these fecal indicator bacteria in streams is primarily from a non-sewage source (soil), current monitoring data are not useful because they cannot be used to determine when streams are really contaminated with sewage. To address this need, we have shown that other alternative fecal indicators (*Clostridium perfringens*, FRNA coliphages) can be used to determine when streams are contaminated with sewage because they cannot multiply under environmental conditions and they are consistently present in high concentrations in sewage (R.S. Fujioka and L.K. Shizumura, 1985, *J. Water Poll. Contr. Fed.* 57:986–992; R.S. Fujioka et al., 1997, *Proc. Water Environ. Fed. 70th Ann. Conf. and Expo.*, 405–411; K. Luther and R. Fujioka, 2002, *WEFTEC 2002 Conf. Proc.*, 75th Ann. Tech. Exhib. and Conf., 12 pp. on CD-ROM).

The identified problem is the potential limitation of our studies because most of the data were collected for the island of Oahu and the results are assumed to be similar for all of the other islands of the state of Hawaii. However, it is well known that the soil composition and geology of the various islands of Hawaii differ because the age of the islands differs. In this regard, the islands arose from the eruption of lava from a single hot spot on the ocean floor. Over time, this hot spot moved eastward, leaving a chain of eight islands. Kauai is the oldest island at 4 to 5 millions years old, and Oahu is the second oldest at 2 to 3 million years old. Molokai, Maui, Lanai, and Kahoolawe, the middle islands, follow in age at about a million years old. Hawaii, the youngest island, is reported to be only 0.7 million years old.

The overall goal of this study is to determine whether environmental monitoring data for fecal coliform, *E. coli*, enterococci, *C. perfringens*, and FRNA coliphages, which have been used to assess the hygienic quality of recreational waters for the island of Oahu, are equally applicable to all of the other islands of the state. The objective of Phase I of this study was to determine whether monitoring data obtained from soil and recreational water samples from the island of Oahu are similar to those obtained from similar types of environmental samples from the island of Kauai, which represents the oldest island. The objective of Phase II was to determine whether monitoring data obtained from soil and recreational water samples taken from the island of Oahu are similar to those obtained from similar types of samples taken from the island of Hawaii, which represents the youngest island. It should be noted that Phase II of this study was not funded, and therefore this report is restricted to Phase I or to assessing the quality of water on the island of Kauai. A no-cost extension was granted for the Phase I work.

Methodology

EPA-approved methods (Standard Methods) to assay for fecal coliform, *E. coli,* and enterococci were used to assay the soil and stream water samples obtained from Kauai. These same water samples were also assayed for *C. perfringens* (J.W. Bisson and V.J. Cabelli, 1979, *Appl. Environ. Microbiol.* 37:55–66) and for FRNA coliphages (J. Debartolomeis and V.J. Cabelli, 1991, *J. Appl. Environ. Microbiol.* 57:1301–1305) using methods developed by EPA. During this study, we traveled to Kauai on several occasions to meet with agency personnel and to obtain soil and water samples. Arrangements were made to have water samples sent to us from Kauai on approximately a monthly basis. The Hanalei watershed and the Nawiliwili watershed were the primary study sites.

Principal Findings and Significance

Kauai differs from Oahu in three significant ways. First, it is an older island. Second, there is greater rainfall there, resulting in more and larger streams. Third, Kauai still relies on cesspools to collect and treat wastewater (this method of wastewater collection and treatment is not used throughout most of Oahu). Cesspools are not satisfactory systems, and some of the inadequately treated wastes from cesspools are expected to contaminate the nearby streams and coastal waters. This study focused on the Hanalei and Nawiliwili watersheds. In this regard, we worked closely with the Clean Water Branch of the state of Hawaii and with environmental organizations on Kauai that are responsible for assessing the water quality at these two watersheds. For the Hanalei watershed, we worked closely with and made presentations to members of the Hanalei Heritage River Program. For the Nawiliwili watershed, we worked closely with and made presentations to the Nawiliwili Bay Watershed Council.

The principal findings and significance of this study are as follows. First, as also observed on Oahu, soil samples from Kauai contained high concentrations of fecal indicator bacteria such as fecal coliform, *E. coli*, and enterococci. The significance of this observation is the identification of the same environmental source of fecal indicator bacteria on both Oahu and Kauai. Second, as also observed on Oahu, the streams on Kauai consistently contained fecal coliform, *E. coli*, and enterococci at concentrations that exceeded hygienic water quality standards. The significance of this observation is the impact of the environmental source (soil) of fecal indicator bacteria, which explains the consistently high concentrations of fecal indicator bacteria in the streams on Kauai. Third, as also observed on Oahu, the concentrations of *C. perfringens* in Kauai streams were low but increased when sewage spill was observed. The significance of this observation is the applicability of monitoring for *C. perfringens* as a reliable means of determining when recreational waters are contaminated with sewage. Fourth, as also observed on Oahu, marine coastal water sites that receive land-based discharges (streams, storm drains) contained elevated levels of fecal indicator bacteria. The significance of this observation is the predictable way in which land-based or nonpoint sources of pollution can be expected to increase fecal bacterial contamination at coastal water sites. Fifth, unlike Oahu, many of the streams on Kauai contained elevated levels of FRNA coliphages. The major significance of this observation is that FRNA coliphages may be the best indicator for the contamination of stream water by wastewater from cesspools. This conclusion is based on the small size and stability of FRNA coliphages, characteristics which enable them to be readily transported through soil to contaminate nearby streams. In summary, the monitoring data for Kauai provided similar results as the monitoring data for Oahu. These results indicate that the conclusions on water quality for Oahu are applicable to Kauai.

For FY 2003, based on nine monthly samples collected from three stream sites within the Nawiliwili watershed, the following conclusions were made. First, the high geometric mean concentrations of fecal coliform (323 to 6,533 CFU/100 ml) and enterocococci (332 to 2,577 CFU/100 ml) are similar to those found on Oahu, confirming that these indicators are not useful for determining fecal contamination. Second, the generally low geometric mean concentrations of *C. perfringens* (1 to 19 CFU/100 ml), except when a sewage spill occurred, are also similar, confirming the results obtained for Oahu that this organism is the best indicator for determining surface contamination by sewage. Third, the low to high geometric mean concentrations of FRNA coliphages (3 to 45 PFU/100 ml) in streams on Kauai are different from the low concentrations in streams on Oahu, confirming that the source of FRNA coliphages in some streams on Kauai is wastewater from cesspools.

Removal of Nitrogenous Aquaculture Wastes by a Wind-Powered Reverse Osmosis System, Year 2

Basic Information

Title:	Removal of Nitrogenous Aquaculture Wastes by a Wind-Powered Reverse Osmosis System, Year 2
Project Number:	2002HI1B
Start Date:	3/1/2002
End Date:	2/28/2005
Funding Source:	104B
Congressional District:	Hawaii 1st
Research Category:	Water Quality
Focus Category:	Nitrate Contamination, Water Supply, Waste Water
Descriptors:	nitrogen, aquaculture waste, membrane, reverse osmosis, water reuse
Principal Investigators:	Clark C.K. Liu

Publication

1. Liu, C.C.K.; J.W. Park, 2002, Water desalination, in McGraw-Hill Encyclopedia of Science & Technology, ninth edition, volume 22, New York, New York, McGraw-Hill, 404-406.
2. Liu, C.C.K.; R. Migita; J.W. Park, 2002, System development and testing of wind-powered reverse osmosis desalination for remote Pacific islands, Journal of Water Science and Technology: Water Supply 2(2), 123-129.
3. Park, S.J.; C.C.K. Liu, 2003, Experimental and simulation of a wind-driven reverse osmosis desalination system, Water Engineering Research 4(1), 1-17.
4. Gang, Q., 2002, Cost-effective aquaculture nitrogen removal by wind-powered reverse osmosis membrane technology, MS thesis, Department of Civil and Environmental Engineering, College of Engineering, University of Hawaii, Honolulu, Hawaii, 186 pages.
5. Liu, C.C.K., 2002. Wastewater reuse, in McGraw-Hill 2002 Yearbook of Science and Technology, New York, New York, McGraw-Hill, 406-409.
6. Liu, C.C.K.; J.W. Park; J. Migita; G. Qin, 2003, Experiments of a prototype wind-driven reverse osmosis desalination system with feedback control, Desalination 150(3), 277-287.

Problem and Research Objectives

Advanced treatment must be provided to wastewater used for freshwater aquaculture in order to meet effluent water quality standards. Because such treatment can be expensive and because freshwater is also increasingly in short supply around the world, an attractive management alternative is to develop a closed aquaculture system that supports effluent treatment and reuse while overcoming obstacles of high treatment cost and a short freshwater supply. The research objectives for FY 2001 and FY 2002 are (1) to investigate the nitrogen build-up in freshwater aquaculture of tilapia, (2) to develop a wind-powered reverse osmosis (RO) nitrogen removal system, and (3) to evaluate the economic feasibility of the wind-powered RO system for removing nitrogen from aquaculture wastes.

The studies on removal of nitrogenous aquaculture wastes by a wind-powered RO system is followed by a second phase of research on a new pollution issue—namely, the discharged concentrate. The mechanisms of the RO membrane system are such that the discharge concentrate will have a higher nitrogen concentration level than that of the untreated wastewater from the fish tank. Thus the concentrate cannot be recirculated in the system; rather, it must be discharged or further treated before it can be reused. The research objectives for FY 2003 and FY 2004 are (1) to further investigate the nitrogen build-up in discharged concentrate from the RO system and (2) to develop a duckweed-based pond system to remove nitrogen from the concentrate.

Methodology

This began as a two-phase project, with each phase scheduled to last one year. The focus of the first year's research (activities and findings reported here) was to study the characteristics of aquaculture waste, especially the concentration of nitrogen at different stages of fish (tilapia) growth. The second year's research was to investigate the performance of nitrogen removal by the reverse osmosis process and to develop a water recirculating system for tilapia production.

The reverse osmosis module of the system separates the wastewater from the fish tank (or feed water) into permeate and concentrate. The high-quality permeate is circulated back to the fish tank and is reused as a freshwater supply. The concentrate is mixed with feed water and is treated again by the reverse osmosis module. As the system operation goes on, the nitrogen concentration in the concentrate becomes higher and must be discharged from the system. As part of the second phase of research, the desirable frequency of concentrate discharge is evaluated, and the process and reuse of waste concentrates by a duckweed-based reactor are investigated.

Principal Findings and Significance

An experimental system, which consists of an aquaculture subsystem or a fish tank for tilapia culture and a wind-powered reverse osmosis treatment subsystem, was constructed in FY 2001 at the research facilities of the Hawaii Institute of Marine Biology on Coconut Island, Oahu, Hawaii.

Water samples were collected from the tilapia culture tank from June 2001 to February 2002. Samples were analyzed in the water quality laboratory of the Water Resources Research Center at the University of Hawaii at Manoa. Table 1 shows the nitrogen concentration data for the aquaculture subsystem. Feedwater is the freshwater provided to the fish tank. Discharge indicates the aquaculture waste flow out of the fish tank. The waste discharge becomes the feedwater for the wind-powered reverse osmosis treatment subsystem. The hydraulic retention time in the aquaculture subsystem or fish tank was about 500 minutes (8.3 hours). During this time, the feedwater and waste discharge rates were both about 73 gal/h (4.6 l/min).

The feedwater provided to the fish tank contained ammonia nitrogen (NH_3-N) at a concentration of less than 0.03 mg/l, whereas the concentration in the aquaculture waste discharge averaged 0.20 mg/l with an unbiased standard deviation of ±0.12 mg/l. The average feedwater nitrate nitrogen (NO_3-N) concentration was 0.17 ± 0.02 mg/l, and the discharge concentration was 0.16 ± 0.02 mg/l. The nitrite nitrogen (NO_2-N) concentration was 0.0012 ± 0.0012 mg/l for the feedwater and 0.0019 ± 0.0015 mg/l for the discharge.

Performance of the reverse osmosis treatment subsystem to remove nitrogen has been evaluated by studying nitrogen concentrations in the feedwater and product water (permeate), as well as by studying the operating flow rate and feed water pressure. Preliminary data indicated that the subsystem removes about 93% of the ammonia and nitrate from the feedwater.

Table 1. Nitrogen Concentrations of Aquaculture Subsystem Under Normal Conditions

Date	NH_3-N (mg/l)		NO_3-N (mg/l)		NO_2-N (mg/l)	
	Feedwater	Discharge	Feedwater	Discharge	Feedwater	Discharge
06/13/2001	UD*	0.19	0.17	0.14	0.001	0.006
06/14/2001	UD	0.14	0.17	0.14	0	0.001
06/15/2001	UD	0.11	0.21	0.17	0.003	0.004
06/21/2001	UD	0.12	0.20	0.16	0.003	0.002
07/10/2001	UD	0.07	0.15	0.13	0.002	0.001
01/07/2002	UD	0.40	0.17	0.17	0.001	0.001
01/09/2002	UD	0.32	0.17	0.17	0.001	0.003
01/17/2002	UD	0.50	0.16	0.16	0	0
01/22/2002	UD	0.23	0.17	0.20	0	0.001
01/24/2002	UD	0.20	0.17	0.18	0.001	0.002
01/31/2002	UD	0.09	0.17	0.17	0.002	0.001
02/05/2002	UD	0.22	0.14	0.16	0	0.001
02/12/2002	UD	0.26	0.16	0.16	0.001	0.002
02/14/2002	UD	0.06	0.18	0.16	0	0.002
02/21/2002	UD	0.09	0.14	0.14	0	0
02/26/2002	UD	0.25	0.12	0.12	0.004	0.003

*****UD = undetectable.

Results of field experiments indicated that the frequency of concentrate discharge is one of the key factors that control the ammonia nitrogen concentration in the concentrate.

Figure 1 shows the changes of ammonia nitrogen concentrations in the feed water, permeate, and concentrate, with a 6-hour concentrate discharge frequency. Comparing the data presented for 4-hour and 8-hour discharging experiments, the peak ammonia nitrogen concentrations in concentrate from 6-hour discharges are 1.09 and 1.49 mg/l, and the peak nitrate concentrations in concentrate are 0.57 and 0.71 mg/l, which proves that the discharging period is a key factor in controlling the concentration levels of the concentrate discharged.

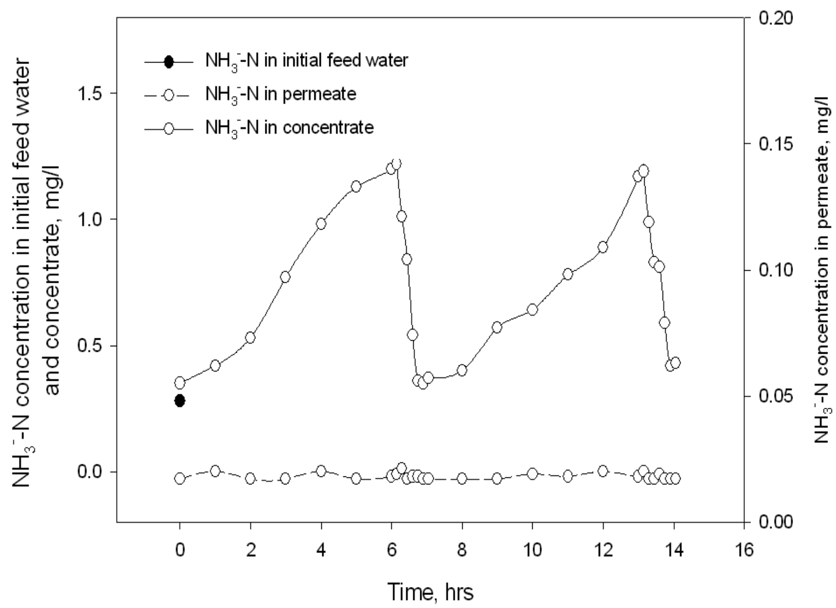

Figure 1. The concentration of ammonia nitrogen in the feed water in the permeate, as well as in the concentrate, with a 6-hour frequency of concentrate discharge and an average ambient wind speed of 5.3 m/s

Results of field experiments also indicated that the freshwater recovery rate would change with the frequency of concentrate discharge and the ambient wind speed (Figure 2).

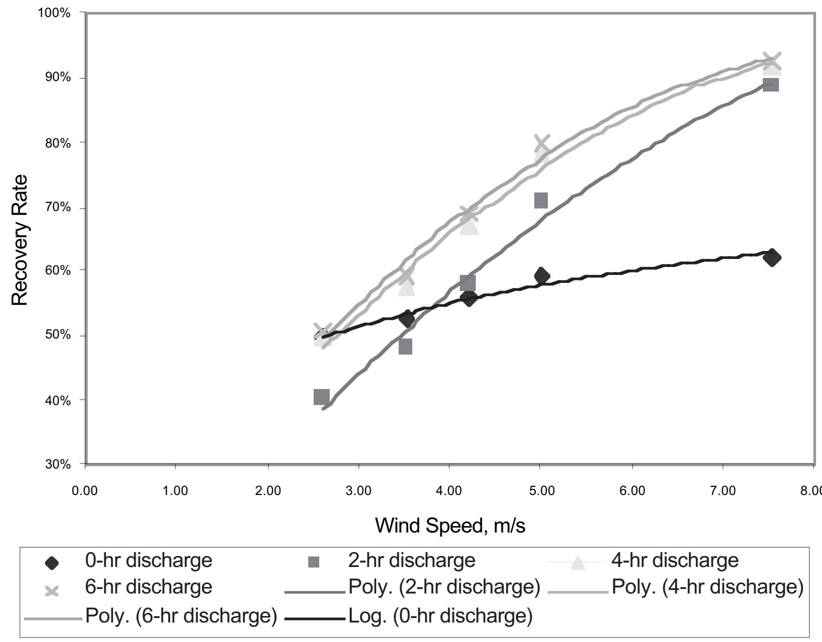

Figure 2. Relationships of freshwater recovery rate and ambient wind speed

Research findings are included in a manuscript entitled "Aquaculture Wastewater Treatment and Reuse by Wind-Driven Reverse Osmosis Membrane Technology: A Case Study on Coconut Island, Hawaii" by G. Qin, C.C.K. Liu, N.H. Richman, and J.E.T. Moncur. The manuscript is currently being reviewed for publication in *Aquaculture Engineering*.

As part of the continuing research effort, a plug-flow bioreactor is being designed for the treatment and use of concentrate (brine) from the reverse osmosis process (Figure 3).

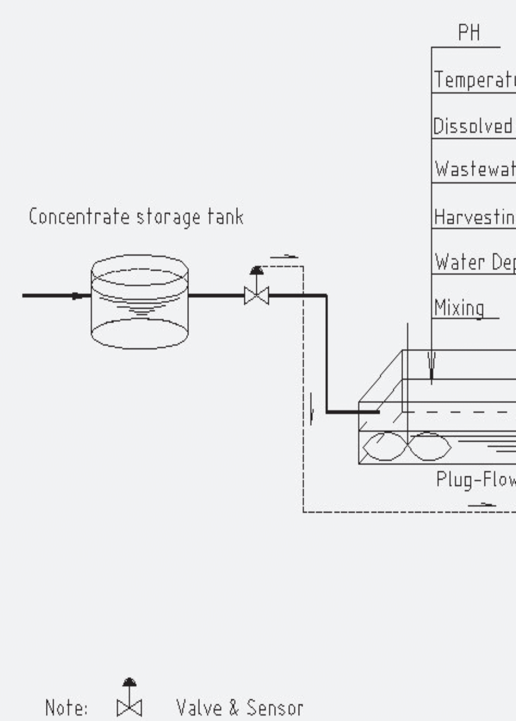

Figure 3. Schematic of plug-flow bioreactor

An Accurate Evaluation of Water Balance to Predict Surface Runoff and Percolation

Basic Information

Title:	An Accurate Evaluation of Water Balance to Predict Surface Runoff and Percolation
Project Number:	2002HI4B
Start Date:	3/1/2002
End Date:	2/28/2005
Funding Source:	104B
Congressional District:	First
Research Category:	Climate and Hydrologic Processes
Focus Category:	Surface Water, Water Quality, Non Point Pollution
Descriptors:	models, runoff, best management practices, vadose zone, ground water, infiltration, recharge
Principal Investigators:	Chittaranjan Ray

Publication

1. Ray, C.; I. Stewart; M. Snehota; M. Sanda; T. Hakonson; B. Harre, An alternate cover for landfill cap in a tropical setting: 1. Study site and automated data collection, paper in preparation for submittal to Water Resources Research.
2. Ray, C.; M. Sanda; C. Miyasaki; T. Hakonson; B. Harre, An alternate cover for landfill cap in a topical setting: 2. Evaluation of water balance, paper in preparation for submittal to Water Resources Research.

Problem and Research Objectives

Hawaii, like many other states, has a number of unlined landfills that are potential groundwater contamination sources. Infiltration control is a major means of reducing leachate generation at unlined landfill sites. Use of synthetic materials for the closure of landfills is quite expensive, especially for small rural communities. Use of alternate capping technologies, such as vegetation caps, may not be suitable in humid areas where the annual precipitation exceeds the evapotranspiration demand of growing crops. However, a combination of natural soil caps and runoff-enhancing structures can be a feasible capping method. Local plants growing on natural soil (clay) caps could transpire a large part of the percolating water. Making a portion of the landfill surface impervious (e.g., by use of rain gutters) and diverting the surface runoff offsite could reduce the entry of water through the landfill cap, thus reducing the potential for leachate generation. A recent demonstration by the U.S. Navy showed that, in tropical areas such as Hawaii, it is possible to cap landfills with natural soil cover if 20% to 40% of the surface area can be covered with rain gutters. However, the amount of error in the prediction was high. In addition to some simplifying assumption for water conduction in capping material, the model used daily water balance for calculating runoff and infiltration. In reality, rainfall in Hawaii occurs over a relatively short period of time. Higher-intensity rains cause significant surface runoff. Averaging a storm event over a day would significantly reduce the intensity, making it appear as if there is no runoff and all water is infiltrating the ground. For groundwater recharge studies, this overestimation of recharge may provide a false sense of security through modeling by implying that a large part of the rainwater is entering the soil in recharge areas and less water is lost through runoff. It is clear that an accurate estimate of the partitioning of rainwater to surface runoff and infiltration components and the subsequent movement of infiltrated water through subsoil media is quite important for a variety of applications.

The objectives of the study are to measure percolate and runoff at frequent intervals at the test plots from natural rain and sprinkler-applied water and to calibrate and test a recharge model and a runoff-producing model against the collected data. These models will provide some insight into the mechanisms of percolate and runoff production in response to specific storm events. They will also indicate if improvements in modeling strategy are needed to better calibrate these models against the collected data. An additional objective is to validate a regulatory model that is commonly used for the closure of landfill caps. The data will also help in the recalibration of the surface runoff and percolate production models and in the study of chemical transport through the soil. Since this is a multi-year study, the activities this year are closely related to the previous two years' effort.

Methodology

The study site is located at the Marine Corps Base Hawaii in Kaneohe, Hawaii. The site, located near a landfill site, has six test plots—all instrumented to collect surface runoff, percolate at a depth of 2 to 3 feet, and soil moisture data. In addition, weather data such as temperature, relative humidity, wind velocity and direction, solar radiation, and rainfall are measured at the test site. The site is instrumented with pressure transducers, flow meters, soil moisture probes, and other sensors that are connected to data-logging devices to collect data at intervals ranging from a few minutes to twice daily. All collected data from the data loggers are downloaded to a computer (remotely located anywhere) via a modem and a cellular phone daily.

The following four tasks describe the methodology involved in the current study.

Task 1. Repair and replacement of aging and malfunctioning sensors and instruments, and instrument calibration (continuation of the previous years' activities)

In order for all instruments to function properly, replacement and recalibrations are continuously needed. Work involves replacement of flow counters, recalibration of pressure transducers, and replacement of level switches and multiplexers. In addition, work involves installing erosion control measures that are needed to prevent sliding of material in various areas of the experimental field and to prevent the material from offsite locations from entering the study area. To calibrate the pressure transducer, each tank is first emptied. Then, a known amount of water is introduced into the tank. The transducer response is recorded as a function of the volume of water that is expressed as the depth of water in the tank. Three separate measurements are made. A line of best fit is drawn to get the slope and the intercept to record the calibration constants.

Task 2. Additional soil hydraulic, vegetation, and evaporation data collection

To use computer models for water balance calculations, additional data (not counting the runoff and leachate data) need to be collected. Some examples include data on weather, soil-water retention, hydraulic conductivity, soil moisture, and leaf area index. Producing water retention curves for soil samples involves taking core samples from the field to the laboratory and measuring the equilibrated pressure and water content of the samples from –5 cm to 15 bars (-15,000 cm) using a combination of tension tables and pressure-plate apparatus. Altogether, 54 core samples were retrieved from various depths to obtain soil-water retention parameters.

A disc infiltrometer (from Soil Measurement Systems) is used to measure hydraulic conductivity at three locations per plot. Because surface soils are affected by cracks, root channels, and other macropore features, the measured hydraulic parameters at the surface can be different from those at deeper depths. Thus, measurements are made first at the soil surface. Then similar measurements are made 15 to 20 cm below the land surface.

A vegetation survey is conducted using the point-frame method in which a frame, which has a groove at every 10-cm interval, spans the width of the plot. A thin metal rod is dropped in each of the grooves. The type of plants that the rod touches is then recorded. Also recorded is what the tip of the rod hits (e.g., soil, litter, or gutter). Approximately 600 points in each 6 m 9 m plot are measured.

Leaf area index can be calculated using two methods. The first method is similar to the vegetation survey technique, except that it uses approximately 40 equally spaced points. The same frame and metal rod are used, but instead of recording which plants the rod touches, the number of live plants with which the rod makes contact is recorded. The 40 points are then averaged to get the leaf area index. The second technique involves tossing a 0.1 m 0.1 m frame randomly onto the plot. All leaves found inside the frame are cut and bagged. The total area of the leaves divided by 0.01 m^2 gives the leaf area index.

Biomass measurements are needed for each plot. By definition, biomass is the amount of living matter; however, for this project, biomass is defined as the amount of living and dead plants. To estimate the biomass, the 0.1 m 0.1 m frame is randomly tossed onto the plot. All plant material within the frame is trimmed and bagged, leaving the roots behind. Each sample is dried at 70˚C in a plant-drying oven and then weighed. The weight of the dried biomass is divided by 0.01 m^2 to get the average biomass per unit area.

A Class A Weather Bureau evaporation pan was setup near the meteorological station. A pressure transducer with fine resolution is used to continuously monitor the loss of water.

Duplicate soil cores from four locations outside the plots and from two locations within the plots are taken for the analysis of soil particle-size distribution. Both the mechanical sieve analysis and the hydrometer settling method are used to get the size distribution of these particles. Particle-size data are then related to soil hydraulic conductivity.

Task 3. Setup of an irrigation system to create artificial rain for water balance measurements

A sprinkler irrigation system was set up on three plots (control, 20% impervious, and 40% impervious) to make artificial rain at a given intensity for desired durations for water balance measurements. Before that, nine automated tensiometers in the three plots were installed to measure soil-water tension as a function of time.

Each plot has a nested tensiometer (at three depths) and four surficial tensiometers. Readings from these tensiometers are taken manually. Also, each plot has four automated (5 to 25 cm) and two manual (5 to 25 cm and 35 to 55 cm depths) time domain reflectometry (TDR) probes for reading water content. The manual probe readings are to be compared with the automated probe readings.

Task 4. Water balance simulations using a regulatory and two event-based (a runoff and an infiltration/percolation) models

The landfill water balance model (HELP-3; P.R. Schroeder, T.S. Dozier, P.A. Zappi, B.M. McEnroe, J.W. Sjostrom, and R.L. Peyton, 1994, EPA/600/R-94/168b, U.S. Environmental Protection Agency, Washington, D.C.) is used to calculate water balance on a daily basis. For the applied irrigation water or the rain from a natural storm, an infiltration/percolation model (HYDRUS-1D, version 2.0, by J. Simunek, M. Sejna, and M. Th. van Genuchten, 1998, IGWMC-TPS-70, International Ground Water Modeling Center, Colorado School of Mines, Golden, Colorado) and a runoff model (KINEROS2, a modified version of the model by D.A.Woolhiser, R.E. Smith, and D.C. Goodrich, 1991, ARS-77, U.S. Dept. of Agriculture, Agricultural Research Service, Washington, D.C.) are used. In the water balance equation, the amount of rain or irrigation water applied is known. In addition, the amount of percolation and runoff are directly measured. Pan evaporation data give an idea about evaporation. Also, the local weather data are used to calculate long-term potential evapotranspiration. Changes in soil-water storage are calculated from the tensiometer/TDR probe readings.

Principal Findings and Significance

Erosion control measures are periodically needed to ensure that water and sediments from offsite do not enter the test site, where most of our leachate and runoff measuring devices are sitting in an excavated area adjacent to a slope. In the past, severe erosion resulted in the formation of gullies. After the addition of erosion cloth and riprap, the slope has stabilized and major erosion is no longer taking place. All gullies have since been plugged.

With continuous repair and replacement, all sensors are working properly. Rainfall frequency data are now collected at 1-minute intervals during rain events, as a result of a modification made to the data logging program. During dry periods, rainfall data are collected only at 15-minute intervals (the same frequency as other sensors).

Retention data for more than 48 samples have been developed between saturation and 15-bar pressure. Most soils appeared to be clayey, and the drainage time for the samples to attain 15 bars of pressure was more than six weeks. Surface hydraulic conductivity, measured using the disk infiltrometer, ranged between 10 and 30 cm/h, with an average of 20 cm/h. The deeper hydraulic conductivity values were close to 5 cm/h. While these values are significantly lower than those measured at the surface, they are much larger (at least one log order) than those used by the U.S. Navy in its earlier study based on core samples.

The leaf area index values were calculated using two techniques (see the "Methodology" section). The leaf area index varied between 0.96 and 2.08, depending on the plot.

The biomass measurements ranged between 210 and 900 g/m^2. This large range is understandable because of the varied nature of plant growth in each of the plots. Some areas of the plots have denser plant cover than other areas. Also, the presence of gutters reduces biomass in certain plots.

Eight rain and irrigation episodes were closely examined for water balance calculations. Most of the rain episodes were limited to three hours. Leachate and runoff were directly measured. Because of the short duration of the events, evaporation data are less likely to be in error. When water content changes estimated from the responses of automated tensiometers were used in the water balance equation, the terms did not balance out. Since measuring rain, runoff, leachate, and evapotranspiration is more accurate than measuring changes in soil water content, we suspect the conversion of pressure readings to water content using the retention curve could have brought in some errors to the water balance equation. Many fine soils exhibit hysteresis in soil-water retention. The retention curve developed in the laboratory was for the drying of samples. If there is hysteresis, then some discrepancy can be introduced in converting pressure readings to water content in the rain event using the drying curve.

We found that leachate amounts predicted using HELP-3 were off by as much as 100%. The underprediction of runoff was greatest for the 40% impervious plot. KINEROS-2 predicted surface runoff very well for the control plot. However, the predictions were off (-27% to 122%) for the partially impervious plots. A reason for this discrepancy is the improper accounting of runoff-producing areas in the model. Although the plots were supposed to be 20% and 40% impervious, in reality they were effective between 5% and 10%, due to interception of overhanging vegetation on the rain gutters. Also, runoff predicted using HELP-3 was lower than the measured runoff values. Leachate production simulation using HYDRUS-1D was better than that with HELP-3. However, the predicted leachate quantities obtained using HYDRUS-1D were still more than the observed values. HYDRUS-1D assumes instantaneous runoff once the rainfall exceeds the simulated infiltration capacity. Measurement errors for soil hydraulic conductivity and soil heterogeneity in the field are other possible types of error.

Two papers and one seminar presentation provide research results of this project. The two papers deal with different aspects of an alternate cover for landfill cap in a tropical setting. The seminar presentation, entitled "An accurate water balance study for the Marine Corps Base landfill test site," was given as part of the fall 2003 seminar series of the Water Resources Research Center, University of Hawaii, Honolulu, Hawaii.

Optimize Aeration, Secondary Clarifier and Disinfection Processes

Basic Information

Title:	Optimize Aeration, Secondary Clarifier and Disinfection Processes
Project Number:	2001HI14S
Start Date:	9/1/2000
End Date:	12/31/2003
Funding Source:	Supplemental
Congressional District:	Hawaii 1st
Research Category:	Engineering
Focus Category:	Waste Water, Treatment, None
Descriptors:	wastewater treatment, aeration, disinfection
Principal Investigators:	Victor D. Moreland

Publication

Problem and Research Objectives

The U.S. Army's Schofield Barracks Wastewater Treatment Plant has a history of not consistently meeting the microbial requirements for discharge into the Waialua Sugar Company irrigation system. The disinfection challenge of reducing the total coliform is that the final effluent quality shall not exceed 23/100 ml for a 30-day median or exceed 240/100 ml in any sample.

The research objectives are (1) to determine whether the chlorine disinfection process is adequate for meeting the microbial requirements and (2) to determine whether the upstream biological process should or can be improved to lessen the burden on the disinfection process.

Methodology

Review existing plant data for process variations that point to a need for process changes. Meet with operating staff, as a team-building effort, to discuss past and current operating guidelines that have been used both successfully and unsuccessfully. Discuss possible changes to the operating guidelines and implement what as a team are felt to be the best testing concepts with the best opportunity for success.

Principle Findings and Significance

The chlorine disinfection process by itself would be inadequate without secondary process improvements.

Control guidance in the past has usually been either mixed liquor suspended solids concentration or mean cell residence time (days). In this effort a somewhat newer approach called total mass (total pounds of suspended solids in the secondary process) was used.

Through experimenting with the process it was found that a far lower than normal dissolved oxygen (0.20 to 0.30 mg/l) was used very successfully, resulting in single-digit effluent total suspended solids (TSS) that has allowed the chlorine disinfection process to meet the disinfection requirements.

In March 2003, we altered the process mode to incorporate an anoxic zone in the first third of each aeration basin, while maintaining the dissolved oxygen (DO) between 0.5 and 1.0 mg/l. The change in DO is in response to increases or decreases in the sludge settling characteristics. The mode has been the most stable used so far, usually generating low single-digit TSS.

The project was completed January 2004, while meeting all the operating objectives and effluent water quality requirements the project team was very satisfied with the results. The facility is now a privatized facility operating with new personnel.

Information Transfer Program

WRRC’s Technology Transfer program continued with a seminar series, project bulletins, a newsletter and occasional assistance in schools. The Tech Transfer office also assisted in arrangements for the 2003 NIWR annual meeting.

Technology Transfer 2003-04

Basic Information

Title:	Technology Transfer 2003-04
Project Number:	2003HI42B
Start Date:	3/1/2003
End Date:	2/28/2005
Funding Source:	104B
Congressional District:	Hawaii 1st
Research Category:	Not Applicable
Focus Category:	Education, Water Quality, Groundwater
Descriptors:	
Principal Investigators:	Philip Moravcik

Publication

WRRC Seminar Series

The Seminar Series is designd to foster communication amongst WRRC researchers, students, and the target audience of government agencies, private sector personnel and members of the public with an interest in water resource issues. A WRRC faculty member is appointed each semester to organize the seminar and recruit speakers on a theme of interest. 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 of emerging water-relatied issues. The following is a list of the seminars presented during the reporting period.

Spring 2003 Seminar Coordinator: James Moncur

3/6/2003 Barry Usugawa, Honolulu Board of Water Supply
Watershed Planning & Management

3/20/2003 Ross Tanimoto, City & County of Honolulu Department of Environmental Services, Wastewater Treatment and Disposal Division
Water Treatment and Effluent Disposal

3/28/2003 Joel D Blum and John D. MacArthur Blum: Professor and Chair of Geological Sciences, Professor of Ecology and Evolutionary Biology and MacArthur: Professor, University of Michigan
Forest Biogeochemistry of Calcium: Acid Rain, Mineral Weathering and a Whole-Watershed Calcium Addition

4/3/2003 James Roumasset, Dept of Economics, University of Hawaii
Economic Modeling of Water Allocation

4/17/2003 Robert Ward, Director, Colorado Water Resources Research Insitute, Colorado State University
Incorporating Sound Science into Water Quality Monitoring

5/1/2003 Denise DaCosta, Honolulu Board of Water Supply
Water Conservation Education Programs

Fall 2003 Seminar Coordinator: Chittaranjan Ray

8/7/2003 Joel Jong, Project Manager for Agricultural Road Stabilization Demonstration Project Hawaii Association of Conservation Districts
Agricultural Road Stabilization Project

9/4/2003 Travis Idol, Natural Resources & Environmental Management, University of Hawaii
Forest Watershed Hydrology

9/18/2003 Clifton Miyasaki, Graduate Student, Civil & Environmental Engineering Department, University of Hawaii
A Water Balance Demonstration Study for an Alternate Cover Material for Landfill Caps

9/25/2003 Peter Vitousek, Department of Biology, Stanford University
The Hawaiian Islands as Microcosm and Model

10/2/2003 Katherine C. Ewel, Senior Scientist, Institute of Pacific Islands Forestry, USDA Forest Service, Honolulu, HI
Understanding Wetland Resources: From Crabs to Watersheds

10/9/2003 Dieter Mueller-Dombois, Professor Emeritus, Botany Department, University of Hawaii
The PABITRA Project: Island Landscapes Under Global Change and the Kahana Ahupua'a as a PABITRA Site Oahu

10/23/2003 Carl Berg, Hanalei River Hui
Hanalei's Modern Hawaiian Ahupua'a Approach to Watershed Management

11/6/2003 Luciano Minerbi, Urban and Regional Planning Dept. University of Hawaii Manoa
Watershed Planning and Ahupua'a Management in Waipio Valley, Hawaii

12/4/2003 Lawren Sack, Botany Dept. University of Hawaii
The "Hydrology" of the Leaf: Linking Structure, Function and Prediction

Fall 2003 Seminar Coordinator: Kaeo Duarte

1/29/2004 Carlos Andrade, Center for Hawaiian Studies, University of Hawaii
Aia i hea ka wai a Kane?

2/5/2004 Neil J K. Hannahs, Director Land Assets Division, Kamehameha Schools/Bernice Pauahi Bishop Estate
Kamehameha Schools Water Resources Management: A Policy for a New Era

2/19/2004 Michael Puleloa, Moloka'i Researcher for The Kia'i 'Aina Ceded Lands Inventory Project
Waiwai O Molokai: A Slideshow Narrative

WRRC Website 2003-2004

WRRC's website (www.wrrc.hawaii.edu) continues to evolve in response to the changing needs of Center faculty. There are pages covering the Center's mission, showcasing some of the Center's recent research projects, an archive of recent Center bulletins, a description of our laboratory facilities, the seminar schedule for the current semester, upcoming conferences and meeting, links to other sites having content deemed to be pertinent to water issues in the state and region, and perhaps most usefully a searchable database of Center reports including titles and abstracts. This feature gives easy access to information about our publications to anyone with internet access.

Increasingly we are using the website to disseminate reports produced by our faculty.

WRRC Bulletins 2003-2004

The Technology Transfer office continues to produce a paper bulletin containing information about Center research in an informal, non-technical format. This bulletin reaches individuals who do not have access to the internet or who wouldn't ordinarily go searching for information about the Center on our website. Three bulletins were produced during the reporting period.

Student Support

Student Support					
Category	**Section 104 Base Grant**	**Section 104 RCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	1	0	0	0	1
Masters	14	0	0	0	14
Ph.D.	4	0	0	0	4
Post-Doc.	1	0	0	0	1
Total	20	0	0	0	20

Notable Awards and Achievements

Publications from Prior Projects

1. 1997HI05B ("Wastewater Treatment for Odor/Nutrient Control") - Articles in Refereed Scientific Journals - Yang, P.Y.; H.J. Chen; S.J. Kim, 2003, Integrating entrapped mixed microbial cell (EMMC) process for biological removal of carbon and nitrogen from dilute swine wastewater, Bioresource Technology 86, 245-252.