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Research Category I

Hydrology, Climatology and Hydraulics

This category encompasses the physical processes governing water transformations through the atmosphere, over land, in the vadose zone, and in natural water bodies, aquifers and man-made conduits. Examples of investigations include studies of precipitation and stream flow; weather patterns; climate modification; micrometeorological processes linking atmospheric water, solar energy, water use by plants (commercial, exotic and native), and available soil moisture; modeling of hydrologic and hydraulic processes; and the development of databases.

Monitoring California Water Resources from Space

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A comprehensive monitoring system for California water resources would be greatly enhanced by the large-scale view afforded by satellite remote sensing. Several current and near-future satellite missions have now demonstrated the capability for monitoring soil moisture, snow water equivalent, heights of inland water bodies (e.g. rivers, lakes, reservoirs) and changes in total water storage. The goal of this work is to exploit these current and emerging capabilities to develop a framework for monitoring California water resources from space.

A comprehensive monitoring system for California water resources would be greatly enhanced by the large-scale view afforded by satellite remote sensing. Several current and near-future satellite missions have now demonstrated the capability for monitoring soil moisture, snow water equivalent, heights of inland water bodies (e.g. rivers, lakes, reservoirs) and changes in total water storage (i.e. the aggregate of all of the snow, surface waters, soil moisture and groundwater). The goal of this work is to exploit these current and emerging capabilities to develop a framework for monitoring California water resources from space. The focus of the our work is on statewide remote sensing of soil moisture, inland water bodies, changes in the mass of the snowpack, and changes in groundwater and total water storage. Specific objectives are to 1) prepare statewide maps of surface soil moisture using the AMSR-E satellite; 2) Estimate monthly changes in the mass of the Sierra snowpack using data from the GRACE satellite; 3) Estimate monthly changes in total water storage for state's the major watersheds using GRACE; 4) Explore the performance of the current generation of ocean (e.g. TOPEX/Jason) and ice (e.g. ICESat) altimeters to monitor the heights of the state's major rivers, lakes and reservoirs; and 5) Estimate changes in groundwater storage by combining GRACE water storage change estimates with AMSR-E soil moisture estimates and state-of-the-art land surface models.

Our first year of research has seen important progress towards goals 1, 3, and 5. Our first surface soil moisture maps prepared from the AMSR-E data have pointed to problems with the inversion algorithm used to derive soil moisture from observed brightness temperature. We have been in contact with the JPL, USDA-ARS and Princeton groups who are working on better soil moisture retrievals. We will repeat this process when the new data become available later this year and complete the mapping and analysis of surface soil moisture variations across the state.

Research on the use of GRACE data for estimating changes in total water storage is progressing well. A key step towards application of the GRACE data towards water resources problems at the relatively small spatial scale of California (by GRACE standards) has been the development of new techniques for utilizing GRACE data at these higher resolutions. This work will now allow, for the first time, monitoring of water storage changes within the major drainage basins and mountain ranges of the state. We are currently working on delineating these GRACE-compatible regions for the state so that we can map the GRACE data to the Sierras, the Central Valley, the coastal regions, etc.

We have also made important progress towards remote sensing of groundwater using GRACE, AMSR and in situ data. In a preliminary study using the hydrologically data rich area of Illinois, we used GRACE and observed soil water to successfully estimate groundwater storage variations. This work opens the door for groundwater remote sensing in the Central Valley aquifer and the Coastal Plain aquifers, which we are now ready to attempt.

Year 2 Plans

Goals for year 2 will be to complete the major objectives of this work. Our plan is to map the total water storage, snow water equivalent and soil moisture to the major drainage basins of the state, to explore the potential of satellite altimetry to monitor surface water variations, and to attempt to monitor groundwater storage variations using the methods from the preliminary study in the Central Valley. An implicit goal is to demonstrate the utility of these data at spatial-temporal scales that are relevant to statewide water resources management.

Publications

Swenson, S. C., P. J.-F. Yeh, J. Wahr and J. S. Famiglietti, A comparison of terrestrial water storage variations from GRACE with in situ measurements from Illinois, Geophys. Res. Lett., 33, L16401, doi:10.1029/2006GL026962, 2006.

Yeh, P. J.-F., S. C. Swenson, J. S. Famiglietti and M. Rodell, Remote sensing of groundwater storage changes in Illinois using GRACE, accepted, *Wat. Resour. Res.* 2006.

Professional Presentations

Ryu, D., J. Famiglietti, T. H. Syed and S. C. Swenson, Basin-scale hydrological cycles from AMSR-E and GRACE, AGU Fall Meeting, San Francisco, CA, Dec. 5-9 2005.

Collaborative Efforts

Our UCI group collaborates with John Wahr and Sean Swenson from the University of Colorado, and with Victor Zlotnicki from the Jet Propulsion Laboratory on GRACE hydrology research. We work with Eni Njoku from JPL, and Tom Jackson and Dongryeol Ryu from the USDA ARS Hydrology Laboratory in Beltsville, MD on AMSR-E soil moisture. We will be working with Tom Painter from the National Snow and Ice Data Center in Boulder on AMSR-E snow water equivalent.

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Feasibility of Snowpack Characterization Using Remote Sensing and Advanced Data Assimilation Techniques

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The implemented snow data assimilation scheme is able to merge multi-scale multi-frequency remotely sensed observations with a distributed snow model to estimate basin-wide snow water equivalent in conditions with deep/wet snow and with light to moderate vegetation cover, factors which generally confound commonly used snow remote sensing retrieval algorithms.

Many semi-arid regions of the world, including California, depend on annual snowmelt for the majority of their water supply. However the primary method for estimating the amount of water stored in the snow pack (snow water equivalent, SWE) is still most often done by field snow surveys. This approach is extremely limited because the survey data are sparse point estimates and because they rely upon regression and comparison to historical measurements.

New methods for estimation of SWE have been developed recently. For the past several decades, inversion of remote sensing data and application of snow models have been used to estimate SWE. However SWE estimates based solely on either remote sensing inversion or snowpack modeling techniques contain large uncertainty. For retrieval methods, the uncertainty lies primarily in the relationship between the snow states and the remote sensing observations. For modeling, errors occur primarily as a result of the propagation of uncertainty in model inputs (e.g., precipitation) to the SWE estimates. It is this uncertainty that motivates the development of the data assimilation approach used in this project.

Data assimilation methods, such as the Ensemble Kalman Filter (EnKF) are used to merge remote sensing observations into a hydrologic model to produce estimates of SWE over the entire basin. The EnKF weighs the relative uncertainty of the model and of the observations and provides an estimate of the state variable as well as an estimate of its uncertainty. This project constitutes a feasibility study for estimating SWE through the incorporation of remote sensing observations in the microwave, visible, and thermal infrared parts of the spectrum into a physically-based snow model.

The first phase of our work focused on the selection and development of the required snow and remote sensing models needed in the data assimilation approach. We have chosen two widely accepted models as the foundation of the data assimilation framework. During the preliminary testing phase we have incorporated more realistic models for the snow grain diameter evolution and snow albedo (reflectivity) that were found to be extremely important parameters in the radiative transfer (remote sensing) model. These model refinements should ultimately significantly improve the SWE estimates. We have applied the model to data in the Mammoth Mountain region in the Sierra Nevada as well as the Rocky Mountains in Colorado. These models have been embedded in a data assimilation framework (EnKF) to test the ability to estimate SWE from remotely sensed microwave radiobrightness observations.

In this study, synthetic experiments were first performed at the point-scale to test the feasibility of the approach. In these tests, synthetic realizations of the remotely sensed observations were used in the assimilation scheme to test whether the true snowpack characteristics could be re-covered under conditions of uncertain initial conditions and precipitation. The method-ology was shown to outperform commonly used retrieval methods and overcome significant biases often seen in precipitation that is directly propagated to model estimates. Based on the successful point-scale experiments, the method was then applied over a 625 km^2 region and showed similarly positive results (Figures 1 and 2).

The primary findings in this study are that the assimilation approach is capable of providing estimates of SWE in cases with i) deep snow, ii) wet snow, and iii) light to moderate vegetation cover. These are three of the primary confounding problems with traditional snow retrieval algorithms. Furthermore the method allows for improvements over traditional modeling approaches that are subject to large input errors due to sparsely collected data in remote mountainous regions. The flexible method developed in the project has the potential to significantly improve water resource characterization and management in California.

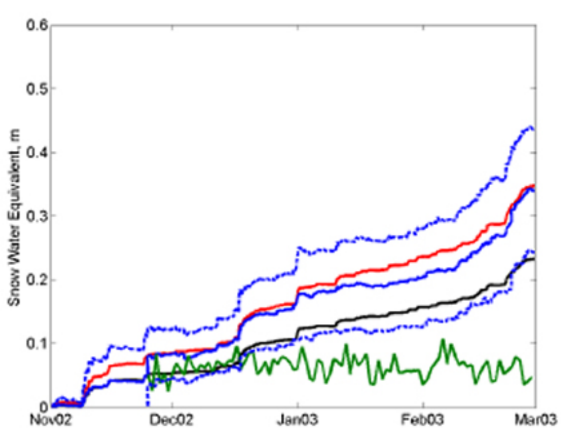

Figure 1. Comparison of the true (red line) spatially-averaged snow water equivalent over the course of the accumulation season to the EnKF ensemble mean/ spread (solid/dashed blue lines), the open-loop (black line), and retrieval algorithm (green line) estimates.

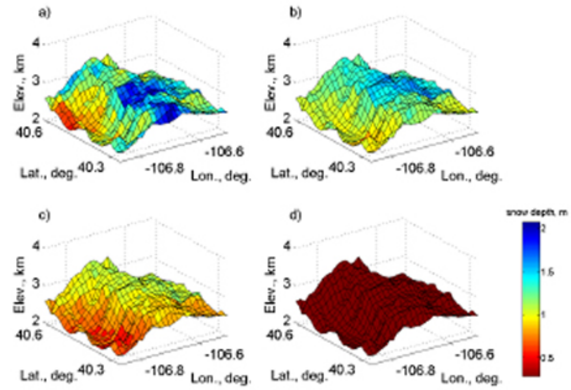

Figure 2. Comparison of spatial maps of snow depth on March 1st for the a) truth, b) ensemble mean from EnKF, c) open-loop simulation, and d) a common retrieval algorithm. The EnKF provides a significant improvement over the open-loop and retrieval estimation approaches.

Publications

Durand, M. and S.A. Margulis, Feasibility test of multi-frequency radiometric data assimilation to estimate snow water equiv-alent, *Journal of Hydrometeorology*, 2006, 7(3), 443-457.

Durand, M. and S.A. Margulis, Large-scale SWE Estimation: Optimal Use of Remote Sensing and Snow Modeling, *Southwest Hydrology*, 2005, 4(2), 20-21, 32.

Professional Presentations

Durand, M., and S. Margulis, Feasibility of snowpack characterization using radio-metric data assimilation: an example of a multi-scale, multi-frequency approach, American Geophysical Union, Spring Annual Meeting, Baltimore, MD, May 2006.

Durand, M., and S. Margulis, Feasibility of snowpack characterization using multi-frequency remote sensing and advanced data assimilation techniques, American Meteorological Society Annual Meeting, San Diego, CA, January 2005.

Durand, M., and S. Margulis, Feasibility of snow water equivalent estimation using the Ensemble Kalman Filter, American Geo-physical Union, Fall Annual Meeting, San Francisco, CA, December 2004.

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Ecohydrologic Effects of Stream Restoration

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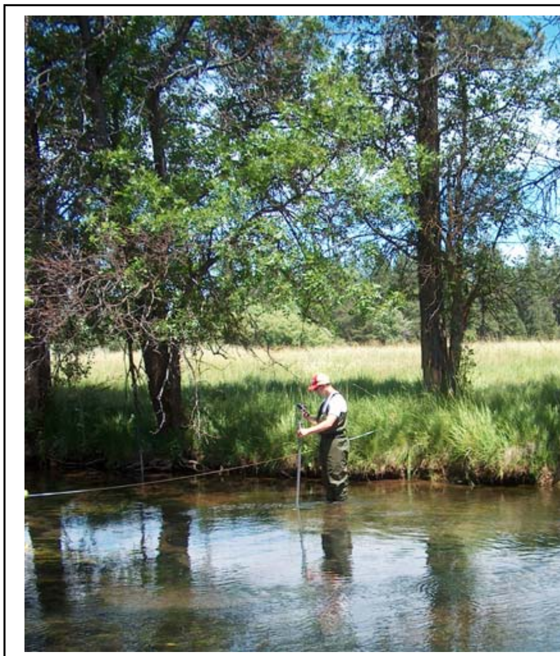
Stream restoration activities throughout California are numerous; however the hydrologic and vegetation responses of these restored systems are poorly understood and rarely documented. The goal of this research is to quantify the hydrologic and ecologic effects of a "pond and plug" stream restoration of a meadow system, in order to improve future design efforts.

Rivers and streams, and their dependent floodplain ecosystems have experienced dramatic degradation throughout California, and much of the world. The growing appreciation of the functions and services that riverine-floodplain wetlands provide and a realization of the need to rehabilitate these degraded systems has lead to a blossoming industry of stream restoration. While stream restoration activities are plentiful, sound scientific basis for various actions, protocols for design, and post-project monitoring and assessment are generally lacking. Specifically, the effects of the popular "pond and plug" channel restoration method upon river-floodplain hydrology and wetland vegetation remain poorly documented. Given the proliferation of these projects, an improved under-standing of the ecohydrologic effects of stream manipulation is vital in improving the methods used to design and assess them.

Through post-project monitoring and assessment, in combination with numerical modeling of an exceptionally well-documented "pond and plug" stream restoration project, this research seeks quantitative answers to two fundamental questions. First, what is the hydrologic response of surface water and groundwater to stream restoration? Second, how will these hydrologic changes impact the distribution of native wetland plant species? This research is focused on a 2.2 mile restored meadow reach of Bear Creek, the largest ephemeral tributary to the Fall River, Shasta County, California. The research plan involves two linked programs, hydrology and vegetation response.

To quantify the impact of the "pond and plug" stream restoration activities on various components of the meadow's hydrology, a hydrologic model of the restored meadow has been constructed, and is currently undergoing calibration. This numerical model consists of a two-dimensional hydraulic model to simulate inundation of the meadow surface coupled with a three-dimensional subsurface model to simulate



Monitoring streamflow

the complex temporal and spatial movement of groundwater throughout the meadow. Atmospheric exchanges due to precipitation and evapotranspiration are also included within the hydrologic model. The first year of UC Center for Water Resources funding allowed for the development/construction of the numerical hydrologic model, in addition to various crucial data collection activities which included, stream flow and water table elevation monitoring, geochemical boundary condition characterization and the refinement of the post-project digital elevation model. During the second year of UCWRC funding, the calibrated and validated hydrologic model will be used to simulate and compare the stream-meadow hydrology under pre- and post-restoration topographic conditions. Expected results include simulation of changes to the: outflow hydrograph (flood peak reduction and delay), depth to groundwater, extent of inundation, floodplain and subsurface storage, as well as evapotranspiration. Preliminary modeling results suggested a significant change to each of these hydrologic components, due to the restoration.


Measuring depth to the ground water table.

The restoration of this reach of Bear Creek caused significant changes to inundation of the meadow surface and depth to groundwater through much of the meadow. These hydrologic changes drove changes in the distribution of wetland plants. In the summer of 2005, data documenting the diversity and abundance of herbaceous vegetation within 185 plots distributed throughout the restored meadow was collected. This vegetation data has been analyzed and several communities (wet meadow, moist meadow, dry meadow, and vernal pool) identified. A predictive vegetation model statistically linking these identified plant communities to the temporal trends in inundation and availability of shallow groundwater is under development. Once complete, this model will be used in combination with the hydrologic model to simulate the areal extent of various vegetation communities present under pre- and post-restoration hydrologic conditions. Expected results include an increase in the distribution of wet and moist meadow communities and a reduction of the dry meadow community type, in addition to an increase in the habitat available for species specializing in vernally wet environments.

The results of this study will aid in many elements of similar stream restoration activities. The integrated ecohydrologic methods utilized will benefit land managers, restoration practitioners and regulators by establishing baseline information regarding the potential benefits of similar projects, as well as developing a new predictive tool to assess potential design considerations. As stream restoration projects increase, and the need to balance the multitude of demands on the precious water resources within the state continues to grow, a better understanding of the hydrologic and ecologic effects of such restoration activities is crucial.

Collaborative Efforts

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Plant Water Use in Owens Valley, CA: Understanding the Influence of Climate and Depth to Groundwater

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There is a long standing controversy in Owens Valley, California about the role of water exports in local vegetation change, particularly the loss of grasslands and the expansion of shrublands. While previous studies have focused on water availability as a primary mechanism of shrub expansion, our measurements of soil organic matter and nitrogen availability indicate that nutrient cycling may be a key variable linking ecology and hydrological processes in the valley.

Owens Valley, California has been the site of redistribution of groundwater for almost 100 years. There is a long standing controversy in the region surrounding the potential influence of groundwater exports on the local vegetation of the valley, which is at the transition between the Mojave and the Great Basin Deserts. In 1991, Inyo County, where Owens Valley is located, and the Los Angeles Dept. of Water and Power signed an agreement stating a goal of water management in the valley must be to avoid changes in local vegetation cover that cannot be acceptably mitigated. To reach this goal, the linkage between hydrology and ecological processes in semi-arid but shallow groundwater ecosystems must be greatly improved, as the impacts of altered hydrology on vegetation is still quite poorly understood.

In this study, we evaluated plant access to groundwater in both grass and shrub species at grass-dominated and meadow-dominated sites in Owens Valley near Bishop, CA. Of particular concern is the loss of grasslands due to encroachment of shrub species such as *Atriplex torreyi* (Torrey's saltbush), *Sarcobatus vermiculatus* (greasewood), and *Ericameria nauseosa* (rubber rabbitbrush). It is has long been assumed that grass species in the valley are more shallowly rooted than shrub species, and are out-competed by shrubs when the water table is lowered beyond the rooting zone. However, the maximum rooting depth of the common species in Owens Valley is unknown. In addition, woody encroachment is a global phenomenon that has been documented in many ecosystems worldwide that do not have shallow water tables. Rather, grazing and climate change are commonly cited reasons for the expansion of shrubs into grasslands. It is not clear if altered hydrology has or will in the future cause a loss of grasslands in Owens Valley.

The isotopic composition of plant stem water can be used to determine if plant water sources are dominated by deep soil/groundwater or shallow surface water. This is because shallow surface water is isotopically enriched (meaning it contains more of the heavy vs. light isotope) due to evaporation. We measured the isotopic composition of grass and shrub stem water along a gradient of decreasing grass cover. We found that grasses do indeed appear to lose contact with the water table in late summer, which corresponds to a reduction in grass transpiration. However, the correlation between access to groundwater and transpiration is not as great as we expected. Grass transpiration is low at our shrub-dominated site regardless of access to groundwater, and shrub transpiration shows spatial and temporal pat-terns that do not correspond well to access to groundwater. Clearly, factors other than groundwater depth and plant access are limiting transpiration in Owens Valley.

Our measurements of soil organic matter (SOM) and nutrient availability indicate that nutrient cycling may be a key variable linking ecology and hydrological processes in the valley. There is a large gradient of soil carbon (C) and nitrogen (N) content across our grass to shrub gradient, with the highest SOM and total N at the grassland site and the lowest as the shrub site (Figure 1). This corresponds well to the pattern of gas exchange at the three sites. It is known that N availability may strongly limit gas exchange due to the high N re-quirement in synthesizing photosynthetic enzymes. For the shrub species at our sites, it appears that plants have constant access to groundwater but have less access to N at the end of the season and at more shrub-dominated sites.

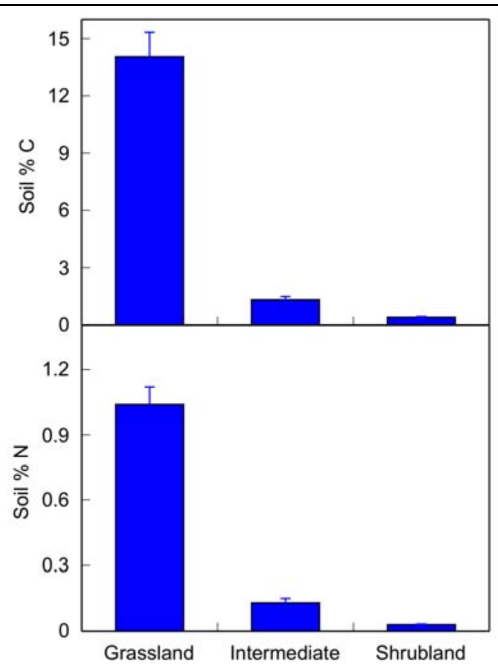

Figure 1. Soil C and N content in the top 5 cm at a grassland, mixed grass-shrubland, and shrub dominated site in Owens Valley.

This finding has led to a new direction in our work. We would like to quantify the link between groundwater depth, vegetation composition, and N cycling in Owens Valley. Nutrient cycling is rarely incorporated into hydrologic models, yet it is likely to be a primary limitation for transpiration. Our results imply that N cycling and availability may improve hydrologic modeling, which is critically important for water resource management. In addition, to explore the management implications of these findings we would like to address the question: does woody encroachment cause a reduction in N availability or do shrubs encroach sites that are already N limited? The answer will provide information about the causes and possible mitigation strat-egies for vegetation changes in Owens Valley.

Collaborative Efforts

We are collaborating with S. Trumbore at UC Irvine to further explore differences in how grasses and shrubs allocate biomass belowground to roots. We are also collab-orating with S. Billings at the University of Kansas to study the biogeochemistry and N cycling in soils from our sites to determine the underlying reasons for differences in N availability. We have written a proposal (currently pending) to NSF with Trumbore, Billings, and J. Famiglietti at UC Irvine to incorporate an improved understanding of ecosystem dynamics into a full hydrologic model of inflows, outflows, and groundwater depth in Owens Valley. The study would contribute to the field of ecohydrology at the interface between the two disciplines.

The Los Angeles Department of Water and Power (LADWP) gave us permission to establish study sites on their property. LADWP, their primary contractor MWH, Inc., and the County of Inyo have all been very helpful and have shared the results of their previous studies in the valley with us.

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Estuarine Landscape Modeling of Suisun Bay

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The long-term viability of estuarine habitats hinges on the successful prediction of geomorphic change and appropriate management response. Climate change in the 21st century is predicted to alter snowpack accumulation in the Sierra Nevada, rainfall in the Central Valley, and therefore sediment runoff to bay ecosystems along the Pacific Coast. We are developing a modeling tool which predicts the geomorphic response of Suisun Bay to climatic changes over decadal timescales.

Suisun Bay, the farthest upstream embayment of San Francisco Bay, provides beneficial habitat to the entire the San Francisco Bay ecosystem. The main goal of this investigation is to develop a modeling tool capable of simulating long-term (>10 year) changes in the shape and depth (i.e. bathymetry) of Suisun Bay. Changes are inevitable as climatic forcing (rainfall, snowpack) is forecasted to become increasingly variable, and as water resource management will need to respond to increasing demand.

Our approach begins with calibrating a hydrodynamic/sediment transport computer model of Suisun Bay. Now that we have validated the model with short-term (<1 year) measurements of water depth, salinity, and sediment flux, we can determine the ideal method for simulating longer periods. These methods include reducing input data (e.g. ocean tides) to representative conditions, simulating only major episodic events (e.g. floods), and extrapolating time-averaged data. We are now in the process of validating the long-term simulations using historical measurements of bathymetric change, which span from 1867 to 1990. The public-domain hydrodynamic model (Regional Oceanic Modeling System, ROMS; http://marine.rutgers.edu/po/) was implemented for this effort. We have made major simplifications to the configuration of the complex Sacramento-San Joaquin Delta (upstream of Suisun Bay). These simplifications appear to be satisfactory; and we can now use widely available historical flow data from the Central Valley watershed as our upstream boundary condition. This greatly simplifies both the hydrodynamic and salinity conditions at that boundary. The successful modeling of water years 1997-1998 and 2002-2004 are a major contribution to the modeling of long-term sediment transport in estuaries.

Publications

Ganju, N.K. and D.H. Schoellhamer, Annual sediment flux estimates in a tidal strait using surrogate measurements. *Estuarine, Coastal and Shelf Science*, 2006, 69, 165-178.

Schoellhamer, D.H., N.K. Ganju, P.R. Mineart, and M.A. Lionberger, Sensitivity and spin up times of cohesive sediment transport models used to simulate bathymetric change, *Proceedings of the 8th International Conference on Cohesive Sediment Transport*, Institute of Lowland Technology, Saga University, Saga, Japan, in press.

Professional Presentations

Ganju, Neil K. and David H. Schoellhamer, Lateral displacement of the estuarine turbidity maximum in a tidal strait, The 8th International Conference on Cohesive Sediment Transport, Institute of Lowland Technology, Saga University, Saga, Japan, September 20-23, 2005.

Ganju, Neil K. and David H. Schoellhamer, Calibration of an estuarine sediment transport model to measured cross-sectional sediment fluxes for robust simulation of geomorphic change, Physics of Estuaries and Coastal Seas, Astoria, Oregon, September 18-22, 2006.

Collaborative Efforts

The validation data from 2004 was collected by the United States Geological Survey Hydrodynamics Group, Sacramento, CA.

Development of the ROMS model has been done in collaboration with Dr. John Warner, U.S. Geological Survey, Woods Hole, MA.

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California-2100: Assessing Future Water Resources over California

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The preliminary results indicate that summer irrigation has a strong effect on the differences between 1996 and 1901 in maximum temperature, surface latent and sensible heat fluxes, surface moisture and equivalent snow water.

This project implemented the initial phase of California-2100 (Cal21), which is aimed at making and evaluating high resolution estimates of climate change over California out to the year 2100. The initial WRC component of this project has been focused on evaluating how well regional climate models reproduce the variations of important components of the water budget for California, and estimating the effects of the increases over the past century in irrigation in California on regional climate, especially snow accumulation.

The utilized regional model is the widely used MM5 running at 30km grid spacing and having 45 levels. There are three primary experimental runs. The modern run (labeled 1996) has boundary conditions from the ERA-40 reanalysis for the period August 1 1995 through September 30, 1996. The atmospheric carbon dioxide concentration is set at 365ppm. An important aspect of this run is that irrigation water is applied to all agricultural regions in a way that approximates irrigation practice. For the other two runs the irrigation rate is set to zero, and the default urban and agricultural land surface types have been modified such that physical characteristics of these types were converted to those of shrub land. For the run labeled Non-Irrig the boundary conditions and carbon dioxide concentration are the same as in the 1996 run. For the run labeled 1901 the carbon dioxide concentration was set to the approximate observed 1901 value of 310ppm and the boundary conditions are constrained to represent the 1900-1901 time period. These boundary conditions are derived from the ERA-40 1995-96 values adjusted using the 1900-99 trends in the monthly means of the output of the highly respected HadCM3 global climate model.

Two major factors have influenced the climate of California in the past century. As elsewhere on the globe the first is global climate change. The second is regional land use changes, associated with the conversion of large blocks of natural vegetation to irrigated agriculture and urban areas. The modeled precipitation and maximum surface temperature difference between the 1996 and 1901 results generally agree with the observed winter and summer trends over the last century. The results also show in summer that irrigation has a strong effect on the differences between 1996 and 1901 in maximum temperature, surface latent and sensible heat fluxes, surface moisture and equivalent snow water.

Professional Presentations

B. C. Weare, Modeling Climate Change in California: Land Surface Changes, Laboratory for Dynamic Meteorology Seminar, University of Paris, VI, July 5, 2005.

B. C. Weare, Climate Change in California: Land Surface Changes, European Geophysical Society, Vienna, Austria, April 5, 2006.

B. C. Weare, Modeling Climate Change in California: Updated Results, Laboratory for Dynamic Meteorology Seminar, University of Paris, VI, April 11, 2006.

Collaborative Efforts

California Energy Commission collaborations: Modeling groups from UCSD (Dan Cayan, PI), UCSC (Lisa Sloan, PI), and UCB (Norm Miller, PI)

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Research Category II

Aquatic Ecosystems

This category encompasses basic observational, analytical and theoretical knowledge about aquatic environments and ecosystems. Research areas of interest include biological, chemical and physical mechanisms that govern the behavior of aquatic ecosystems, including the classification, transport and impact of pollutants. Also included are constructed ecosystems for water reclamation; wetland management; impacts of land use practices on aquatic habitats; role and effect of non-native species, and reconstruction ecology.

Hydrological Regimes, Pond Morphology, & Habitat Use: Predicting the Impact of a Pathogen

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We are investigating why populations of mountain yellow-legged frog in some parts of the Sierra Nevada are experiencing rapid die-offs as a result of chytridiomycosis, a newly-identified fungal disease of amphibians, while other populations are persisting with the fungus. Mark-recapture field surveys have shown that frogs at the persistent sites can survive with the disease, experiencing only mild infections. Laboratory experiments have revealed that this difference in disease outcome is unlikely to be due to differences in fungal virulence or frog susceptibility between areas.

Declines in amphibian populations have been reported throughout the world in recent years. A number of factors have contributed to these population declines, including disease, introduced species, habitat loss and alteration, and climate change. Chytridiomycosis is a potentially fatal disease of amphibians caused by the chytrid fungus, *Batrachochytrium dendrobatidis*, which has appeared recently in the aquatic habitats of California and throughout the world. In portions of the Sierra Nevada Mountains of California, the disease is causing rapid die-offs of mountain yellow-legged frogs, *Rana muscosa*, a threatened native frog species. In other areas of the Sierra, infected populations of *R. muscosa* appear to be persisting with the fungus. In this study we are investigating why the fungal pathogen is having different outcomes on frog populations in different California watersheds.

Laboratory Experiments: A laboratory experiment conducted this year corroborated our previous years' findings that differences in fungal strain and/or differences in frog susceptibility are not responsible for the different population-level impacts of the disease at the different sites.

In this experiment we exposed subadult *R. muscosa* from either northern (persistent) sites, or southern (die-off) sites to *B. dendrobatidis* strains from each type of site. We found no difference between any of the source frog x source fungus location treatments in (a) the fractions of frog individuals that became infected from a standardized dose of the fungus, or (b) resulting frog mortality due to the fungus.

Field Surveys: During summer of 2006 we continued the field surveys started in the summers of 2004 and 2005 at sites in the Sierra Nevada experiencing *R. muscosa* die-offs due to chytridiomycosis, and sites with *B. dendrobatidis* present with persistent *R. muscosa* populations. We continued to use a non-destructive, quantitative PCR technique to determine the infection status (presence/absence of *B. dendrobatidis*) and infection level (fungal loads) of *R. muscosa* individuals. We marked adult *R. muscosa* and recaptured and re-swabbed the same individual repeatedly. We have found additional evidence that infected frogs at die-off sites carried very high fungal loads, while at persistent sites the infected frogs were experiencing only low to moderate infections. As in the previous year, we found that at the persistent infected sites, some adult *R. muscosa* lost the infection through time, and many infected individuals survived over the long overwintering period.

Model Development: The results of our laboratory experiments and field surveys have led us to direct our future research efforts towards understanding the fungal load dynamics within individual frogs. We are currently developing mathematical models to investigate the effects of fungal load on population persistence.

Professional Presentations

Briggs, Cheryl, and Lara Rachowicz, Quantifying the *B.d.* transmission function in *Rana muscosa*: An experimental/maximum likelihood approach, Integrative Research Challenges in Environmental Biology grant meeting, Arizona State Univ., Tempe, AZ, November 2005.

Briggs, Cheryl, Jess Morgan, and John Taylor, *B.d.* Population Genetics in the Sierras, Integrative Research Challenges in Environmental Biology grant meeting, Arizona State Univ., Tempe, AZ, November 2005.

Briggs, Cheryl, How do disease processes differ between persistent and non-persistent populations?, Workshop: Restoration Plans for the Mountain Yellow-Legged Frog, Yosemite National Park, CA, January 2006.

Briggs, Cheryl, Using mathematical modeling to understand disease impacts at the local and metapopulation scales, Workshop: Restoration Plans for the Mountain Yellow-Legged Frog, Yosemite National Park, CA, January 2006.

Briggs, Cheryl, Diseases in landscapes: Investigating the population-level consequences of two emerging infectious diseases in California, University of California, Santa Barbara, CA, March 2006.

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Heavy Metal: Phytoplankton Interactions in San Francisco Bay

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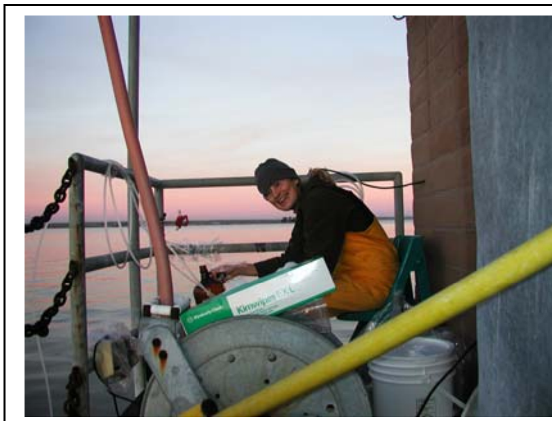
A study is being conducted to determine the interactions of heavy metals with phytoplankton blooms in San Francisco Bay, because some metals (notably copper) approach maximum water quality criteria and may be controlling primary productivity. Results from this study concur with previous copper speciation studies and indicate that most of the copper in the Bay is not available to the plankton, and is therefore not limiting its growth. Phytoplankton blooms, however, have been found to deplete other metals from the water (manganese, lead and nickel), and may thus help entrain those metals within the estuary.

This project addresses one of the principal concerns with the health of San Francisco Bay: whether its primary productivity, or algal growth, is controlled by toxic levels of copper or other metals. Copper has been of special concern, since its concentrations in the Bay have been found to approach and sometimes even exceed both state and federal water quality criteria. Consequently, the influence of copper on algal blooms in the Bay is being analyzed.

Results from those analyses indicate that while copper levels in the Bay may be relatively high, they do not adversely impact primary productivity. This apparent inconsistency is attributed to the presence of dissolved organic material that strongly binds with the copper and makes it unavailable to phytoplankton. These findings are consistent with previous studies of the organic speciation of copper in the Bay. Consequently, this study adds to the evolving understanding that current water quality criteria for copper in estuarine waters need to modified for San Francisco Bay.

Conversely, the study has shown that algal blooms decrease, at least temporarily, dissolved concentrations of other potentially toxic elements, including manganese, lead and nickel. Lead appears to be sorbed onto the plankton surfaces during a bloom, rather than assimilated within the plankton. However, after the algal bloom ends and the plankton decay, lead, manganese, cobalt, and zinc are released back to Bay waters. Consequently, the cycling of those and other heavy metals within the Bay are closely intertwined with the growth and decay of phytoplankton within the Bay.

Information being developed in this study will be of use in determining what factors are regulating both the primary productivity and the concentrations of toxic metals in San Francisco Bay.



Graduate student, Allison Luengen, sampling in San Francisco Bay.

Publications

Luengen, Allison, Peter Raimondi, and Arthur Flegal, Contrasting biogeochemistry of six trace metals during the rise and decay of a spring phytoplankton bloom in San Francisco Bay. *Limnology and Oceanography*, (in press).

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Collaborative Efforts

The research is being conducted in collaboration with researchers at the United States Geological Survey, who provide ship time and in kind sampling and analyses, as well as comments on the interpretation of our results. Complementary data on trace metals in the Bay are being provided by the San Francisco Regional Monitoring Program, which is administered by the San Francisco Estuary Institute with guidance and support provided by the California State Water Resources Control Board, other state and federal agencies, industry, and environmental organizations.

San Francisco Bay

Investigating the Role of Nitrogen Fixation and Denitrification in a Highly Eutrophic Southern California Estuary

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This project seeks to expand on our knowledge of nitrogen cycling and processing in highly eutrophic estuaries of southern California. Preliminary results of seasonal field surveys and three manipulative experiments suggest that the rates of nitrogen fixation are extremely variable and depend on both abiotic and biotic factors.

Our research takes place in the Upper Newport Bay Ecological Reserve, a protected estuary in Newport Beach, California. Estuaries are critically important habitat to many species of plants, birds and fish, including several endangered and threatened species. They also perform ecosystem services such as protecting the coastline from erosion and filtering nutrient rich water that enters the system as runoff. These services are especially important as urban development continues, though few functional coastal marshes remain in southern California. The estuaries that do remain are threatened by eutrophication that results from excessive nitrogen loading from developed watersheds.

Our objective is to investigate the microbial processes of nitrogen fixation and denitrification that occur in the sediments of the estuary. Nitrogen fixation is a process by which nitrogen from the atmosphere can be converted to ammonium, thus becoming usable by plants. Denitrification can effectively remove nitrogen from the environment by converting nitrate into atmospheric nitrogen and releasing it back into the air. Since these processes can add or remove nitrogen, they have the ability to affect nutrients in the water and sediments and therefore can affect the presence of plants and algae in the estuary.

Surveys of the estuary took place in March 2005, Sept 2005, Feb 2006, and Sept 2006 and included sampling the intertidal mudflat along 5 locations in each of two tidal creeks. During each survey, sediment was taken for nitrogen fixation and denitrification measurements. Samples were also taken to determine other characteristics of the sediments, such as sediment type and nutrient content, organic material present, and water nutrients. This will allow us to determine any correlations between the nitrogen processing rates and ecosystem characteristics.

Graduate student, Tonya Kane, collects sediment samples during the September 2006 survey.

It is clear from the surveys that there is a great deal of variability within the estuary. Some sites exhibit high nitrogen fixation rates, while others show little to no nitrogen fixation activity. We expect to see that nitrogen fixation rates will correlate with abiotic and biotic factors. Rates are hypothesized to be higher in areas of decreased nitrogen supply from the water and surrounding sediments. Denitrification rates are not yet available, though they are expected to be highest in areas with higher nitrate concentrations and higher organic material content.

Three field experiments were also performed during the past year. In July 2005 we executed a nutrient experiment to test the response of nitrogen fixation and denitrification rates after exposure to nutrient enriched water treatments, including enhanced nitrate and phosphorus levels. This simulates estuary conditions as nutrient loading into the system continues to increase. In July – August 2005 we performed a sediment transplant experiment to investigate how microbial nitrogen processing rates are affected by differences in sediment types. In June – July 2006, a 40-day long field experiment investigated how the presence and density of green macro-algal mats, often a product of nutrient enrichment, affect nitrogen fixation and denitrification rates and other sediment and water characteristics beneath the algal mats.

A row of cages used for the algal mat experiment during low tide.

Initial analysis of the sediment transplant experiment shows an effect of sediment types on nitrogen fixation rates when sediments were transplanted to the same location and received the same tidal flushing and exposure to water nutrients. Preliminary results of the nutrient experiment suggest nitrogen fixation rates vary based on nutrient treatment. No results are available at this time for the macroalgal mat experiment.

This research will contribute to our basic understanding of how nitrogen cycles through the Upper Newport Bay Estuary and will provide insight into other southern California estuary systems. It is important to understand these processes, as few estuaries remain and they may function differently than east coast estuaries, which are much different in structure and climate. Understanding nitrogen cycling in these systems could allow policy makers to make more informed decisions regarding the regulation of nutrient inputs into these systems. These processes that add and remove nitrogen from estuarine ecosystems are especially important as nutrient loading and subsequent eutrophication will only increase in the future.

Collaborative Efforts

Determination of rates for nitrogen fixation and denitrification requires a Gas Chromatograph to measure gas concentrations obtained during assays. Dr. Doug Capone at the University of Southern California has allowed us to use his equipment. He and members of his laboratory have been very helpful in teaching us the techniques to measure these characteristics.

This work has also fostered collaboration with the Southern California Coastal Water Research Project (SCCWRP). In June 2006 a proposal was written to the San Diego Regional Water Quality Control Board to incorporate some of the questions we have been asking in the Upper Newport Bay Estuary to a more integrative project in San Diego Lagoon.

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Understanding the Spatial and Temporal Patterns of Wetland Evapotranspiration and Primary Production

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Both scientists and the public recognize the importance of wetlands, but understanding of the ecological processes that control the functioning of California wetlands is lacking. We are working at the University of California, Irvine's San Joaquin Freshwater Marsh to understand the ecological controls on wetland carbon, energy and water vapor exchange, and to explain why the marsh's vegetation varies dramatically from one year to the next.

Both scientists and the public recognize the importance of wetlands. Economists estimate a hectare of wetland provides approximately $14,000 in goods and services a year; the citizens of California have demonstrated support for wetland protection by voting for bond measures. At the same time, the biological, chemical and physical processes that control the carbon, nutrient and water cycles of California wetlands remain poorly understood. Searches of the scientific literature indicate a lack of research on the biogeochemical and hydrological cycles of California Tule Marshes. The disconnect is obvious: scientists and the public recognize wetlands as critically important, but understanding of the ecological processes that control the functioning of California wetlands is lacking.

We are working at UCI's San Joaquin Freshwater Marsh to better understand the ecological controls on wetland carbon, energy and water vapor exchange. The San Joaquin Marsh is an 82-ha *Typha latifolia* and *Scirpus californicus* remnant of a large historical wetland. The marsh is located on the UCI campus, allowing easy access and facilitating undergraduate and graduate student training. Our UCWRC-funded research has three goals. (1) To understand the rates of and controls on marsh evapotranspiration (E_t) and to determine whether wetlands have atypically high rates of evaporation. (2) To understand why wetland vegetation is capable of extraordinarily high rates of growth (Net Primary Production or NPP). (3) To understand why the marsh's E_t and NPP vary markedly from year to year.

Our research uses the eddy covariance technique to measure the exchanges of CO_2 (F_{CO2}) and water vapor (E_t) between the atmosphere and a few hectare patch of marsh. Measurements at the marsh indicate only moderate rates of E_t, which are broadly comparable to those of nearby grasslands, and very high rates of NPP, which are comparable to those of tropical forests. A longer-term look at the observations indicates that F_{CO2} and E_t fluctuated dramatically from year to year, with high photosynthetic uptake of CO_2 in summer 2000 and 2003, moderate uptake in 1999, low uptake in 2001, 2002, 2005 and 2006, and extremely low uptake in 2004. The midsummer rate of evapotranspiration also fluctuated dramatically, with high E_t in 2000 and 2003, moderate E_t in 1999, low E_t in 2001, 2002, 2005 and 2006, and negligible E_t in 2004. The interannual shifts in F_{CO2} and E_t were only partially a result of variation in flooding. While the extremely low rates of CO_2 uptake and evaporation observed in 2004 were a result of drainage to reduce mosquito habitat, the low rates observed in 2001, 2002, 2005, and 2006 occurred despite the presence of ample water. We do not understand why the marsh's vegetation has varied dramatically from one year to the next.

In the last year, we started a series of field experiments to better understand why plant growth varies from year to year, and further investigated the use of remote-sensing to place the oscillations into a larger context. A continuous 20-year record of Landsat images for the marsh was assembled and calibrated. The images were then used to construct a 20-year record of the marsh's mid-summer Normalized Difference Vegetation Index (NDVI), a measure of vegetation density. The record of NDVI since 1999 shows excellent agreements with the simultaneous measurements of F_{CO2} and E_t at the marsh – years with high F_{CO2} and E_t also have a high NDVI.

Analysis of the longer time record of NDVI shows that the oscillations in marsh activity observed since 1999 occur throughout the Landsat time series. This analysis has provided evidence that the patterns observed since 1999 are not atypical for the San Joaquin Marsh. Moreover, a tool that will be used to determine whether other wetlands also show large year-to-year oscillations is under development. In the long term, our research will have practical implications for efforts to manage and restore wetlands, and possibly also for efforts to use wetlands for natural water treatment.

Publications

Goulden, M.L, Litvak, M.E., Miller, S.D. Factors That Control Typha Marsh Evapo-transpiration. *Aquatic Botany*, in press.

Collaborative Efforts

Clara Tinoco from the Universidad Nacional Autónoma de México worked on the San Joaquin Marsh project while on sabbatical.

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Using Marine-Derived Nitrogen in Tree Rings to Assess Nutrient Flux and Salmon Escapement

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Our research uses long-lived riparian trees to determine historic inputs of salmon vectored marine-derived nutrients to individual watersheds. By examining the stable nitrogen isotope ratios of annual growth rings, we are able to infer changes in salmon abundance over time and reconstruct historic returns for periods where no such information exists.

Although it is generally accepted that anadromous salmon and trout populations have declined throughout California, trends for individual watersheds are largely based on incomplete or unreliable data and provide little basis for estimating the true extent of the decline. This is especially true in small coastal basins where continuous records of salmon escapement (i.e., the number of fish that return to freshwater to spawn) rarely exceed 10 years and stock-specific population trends are generally unknown.

Our research uses long-lived riparian trees to examine current and historic inputs of salmon transferred marine-derived nutrients to coastal watersheds. A product of living and feeding in the Pacific Ocean is that the tissues of adult anadromous salmon are uniquely enriched with the heavier isotopic forms of many biologically important elements (e.g., nitrogen, carbon, and sulfur) relative to terrestrial or freshwater sources of these same elements. When mature salmon return to their natal streams and die after spawning, these heavy isotopes are liberated during carcass decomposition and ultimately incorporated into both aquatic and terrestrial ecosystems.

Riparian plants, in particular, may greatly benefit from annual inputs of marine-derived nutrients. Salmon carcasses contain many nutrients essential for plant growth and often provide a large fraction of the nitrogen sequestered by riparian trees. By determineing the annual growth and stable nitrogen isotope composition ($^{15}N/^{14}N$; $\delta^{15}N$) of riparian trees, we are able to infer changes in salmon abundance over time and reconstruct historic salmon returns for periods where no such information exists.

Our previous research demonstrated that conifer trees growing adjacent to anadromous salmon streams readily sequestered and incorporated marine-derived nitrogen when available. In fact, annual tree growth, stable nitrogen isotope ratios and wood total nitrogen content were all found to positively correlate with the number of anadromous salmon that returned to spawn the previous year (i.e., a one year time lag existed between salmon-derived nitrogen delivery and tree response).

This past year we focused our research efforts on the Waddell Creek watershed (Santa Cruz County). In addition to supporting populations of both coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*O. mykiss*), this coastal basin contains the necessary combination of mature trees and years of known salmon escapement that allow us to validate our reconstructions. Furthermore, the presence of two long-lived tree species at Waddell Creek (Douglas fir and coast redwood) provides the unique opportunity to evaluate and contrast annual variation in marine-derived nitrogen incorporation among members of the same riparian community.

In the laboratory, increment core samples were prepared and processed using standard dendrological techniques. All cores were subsequently cross-dated and ring widths were measured using a digital image analysis system. In addition, we continued to refine methods for removing soluble forms of nitrogen (primarily those in sap residues) prior to stable isotope determination. Recent research suggests that nitrogen molecules may be extremely mobile in the xylem of some tree species and such mobility could potentially confound interpretation of marine-derived nitrogen availability at the time of ring formation.

The ability to reliably measure marine-derived nitrogen in tree rings has tangible ecological significance for California's salmonid restoration efforts. Long-lived riparian tree species may potentially serve as valuable records of past biological events such as salmon declines or extirpations. Moreover, if predictable relationships between tree ring $\delta^{15}N$ and salmonid escapement can be routinely derived, it then becomes possible to reconstruct historic salmon returns for the many watersheds where mature streamside trees still exist and escapement records do not.

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Non-Native Fish in Mountain Lakes: Effects on a Declining Amphibian and Ecosystem Subsidy

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2006 was the final year of a 4-year ecosystem-level research project assessing the effects of fisheries management options on distribution and abundance of fish, amphibians, emerging aquatic insects, birds, reptiles and bats in wilderness lake basins. We found that non-native trout presence suppresses the numbers of the declining Cascades frog and other amphibians, as well as large-bodied aquatic insects such as mayflies and caddisflies. After trout removals, these groups show a marked increase in abundance.

Management of water resources in wilderness areas is a challenge to State and Federal agencies because of mandates to protect native species and ecosystems, while providing recreational and economic opportunities for the public. Sport fish have been introduced to many formerly fishless waters in public lands throughout the western USA. The resulting fisheries foster recreational use of wilderness, however, widespread fish introductions have been implicated in the decline of several amphibian species including sensitive species such as the mountain yellow-legged frog and the Cascades frog (a Species of Special Concern in California). Non-native trout prey upon amphibians and aquatic insects. The adult stages of aquatic insects and amphibians are major prey items for bats, birds, snakes, and other terrestrial insectivores.

Our goal is to better understand the consequences of agency fish stocking policies regarding impacts to the native fauna that live in the lakes or feed on the insects and amphibians that emerge from the lakes (Figure 1). Quantitative information on faunal changes and recovery will be supplied to agencies for use in wilderness water resource management planning.

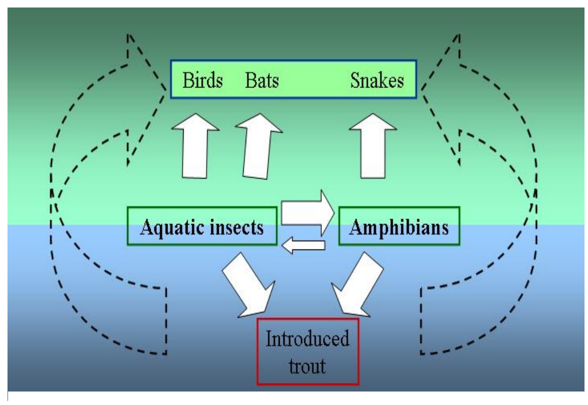

Figure 1. Schematic of wilderness lake study system. White arrows represent energy flow and dashed arrows represent potential indirect effects.

2006 was the final summer of data collection for our 4-year research project assessing the effects of wilderness fisheries management options on distribution and abundance of fish, amphibians, emerging aquatic insects, birds, reptiles and bats.

We collected pre-treatment data in 2003 at all basins and began trout removal from four fish removal basins in the fall. In the following three summers we conducted repeat sampling of the 16 study basins.

In 2003, large-bodied insects, frogs, and garter snakes (*Thamnophis sirtalis*) were all less abundant in stocked sites compared with historically fishless 'control' basins. Over the following summers, the number of Cascades frogs increased in the fish removal basins (Figure 2). During the summer of 2006, we discovered fingerling brook trout in one fish-removal lake where frogs did not significantly increase in abundance, suggesting that we did not eradicate trout in that lake and remaining fish successfully reproduced in the fall of 2005. Mayfly and caddisfly numbers have increased in the fish removal lakes in the years following fish removals. We did not see significant changes in abundance of common garter snakes at fish removal lakes in three years, but expect that numbers may increase in the future.

Our work will be vital to policy development for protecting and managing biodiversity in the extensive montane wilderness areas in the western United States. In addition, this project has great relevance to developing ecological theory. Ecologists have recently recognized the importance of 'ecosystem subsidies', which are flows of nutrients and organisms across the borders between adjacent ecosystems, such as water bodies and terrestrial habitats. This study will show whether a predator introduced into one community affects the level of subsidy flowing into an adjacent community.

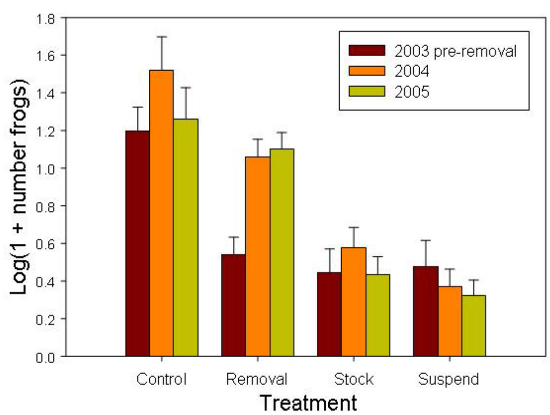

Figure 2. 2003-2005 yearly summary of Cascades frog counts (subadults and adults) collected during repeated summer visual encounter surveys. Error bars represent +1 standard error.

Publications

Welsh, H. H., K. L. Pope and D. Boiano. 2006. Sub-alpine amphibian distributions related to species palatability to non-native salmonids in the Klamath mountains of northern California. *Diversity and Distributions* 12: 298–309.

Professional Presentations

Pope, K. L. and S. P. Lawler. Introduced trout affect ecosystem subsidy and a threatened frog. Ecological Society of America Meeting, Montreal, Canada. August 8, 2005.

Pope, K. L., S. P. Lawler and H. H. Welsh. Effects of Fish Stocking and Fish Removal on Cascades Frog (*Rana cascadae*). Declining Amphibian Populations Task Force, Arcata, CA. January 12, 2006.

Pope, K. L., S. P. Lawler and H. H. Welsh. Introduced trout affect ecosystem subsidy and a threatened frog. Bay Area Conservation Biology Symposium, San Francisco, CA February 4, 2006 and Western Section of the Wildlife Society Annual Conference, Sacramento, CA. February 9, 2006.

Pope, K. L., S. P. Lawler and H. H. Welsh. Effects of trout stocking and removal on Cascades Frogs and other native species. Annual Conference of the California-Nevada Chapter of the American Fisheries Society, San Luis Obispo, CA. April 1, 2006.

Collaborative Efforts

This large-scale project was a collaborative effort with UC Davis, California Department of Fish and Game (CDFG) and the US Forest Service (USFS), made possible by assistance from our granting agencies including CDFG, UC Center for Water Resources, National Science Foundation, and UC Davis Wildlife Health Center. Expertise, time and equipment were contributed to the project by: Dr. Hartwell Welsh and Dr. Don Ashton, USFS Redwood Sciences Laboratory; Betsy Bolster and Bernard Aguilar, CDFG; and John Alexander and Nate Seavy, Klamath Bird Observatory.

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Nutrient Deposition and Food Web Alteration in High Sierran Lakes: Microbial Community Response

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Growing evidence for ecosystem-scale impacts to remote lakes of the Sierra Nevada by nutrient deposition and fisheries manipulations demands an understanding of the role of microbes in these systems. Our initial research indicates a remarkably active and diverse bacterial community in lakes throughout the region. Recent experiments demonstrate that microbial communities in high-elevation Sierran lakes respond rapidly and strongly to phosphorus enrichment, indicating that continuing deposition of this nutrient may lead to significant changes in the rate of organic matter metabolism and overall ecosystem function of these lakes.

High-elevation lakes of the Sierra Nevada, once considered isolated from human impacts, are increasingly experiencing the effects of human activities. Nutrient loading, the result of increasing atmospheric deposition, and the stocking of non-native trout, halted in National Parks but continuing on Forest Service lands, are major anthropogenic impacts to these remote ecosystems. The ecological impacts of both trout stocking and atmospheric pollutants have been studied in high-elevation lakes of the Sierra for nearly two decades, and have been shown to impose significant and lasting impacts at a regional scale, including loss of endangered species, alterations to algal productivity, and changes to zooplankton populations. Connecting these shifts to ecosystem function and biogeochemical cycling is necessary for understanding and predicting ecological impacts in these lakes, yet this has not yet been a focus, despite the documented sensitivity of alpine lake ecosystems to even minor changes in water chemistry or nutrient availability. In oligotrophic (low-productivity) aquatic ecosystems, including most alpine lakes worldwide, the microbial food web (bacteria and their protozoan grazers) is predicted to dominate the metabolism of carbon, nitrogen, and phosphorus. Our research is investigating potential regional ecosystem impacts of eutrophication and trout introductions by examining the role of microbes in the structure and function of Sierran lakes.

Work in 2005-2006 focused on experimental assessment of the microbial response to predicted levels of atmospheric nutrient deposition. Experiments were conducted in Emerald Lake (Sequoia National Park) using *in situ* mesocosms amended with nitrate and phosphorus to examine how bacterial community composition and metabolic rates would be affected by increased availability of inorganic nutrients. Initial phylogenetic sequencing work to identify the species composition of bacteria in Emerald Lake was also completed. In addition, we continued year-round sampling of microbial and biogeochemical variables in Emerald Lake to establish a baseline understanding of bacterioplankton communities and insight into links between bacterioplankton dynamics and seasonal physical and chemical parameters. A second annual survey of six fishless and trout-stocked lakes in Humphrey's Basin

(Inyo National Forest) was conducted in mid-September of 2005 to evaluate differences in bacterioplankton and organic matter stocks attributable to the presence or absence of introduced trout.

Key findings from this second year of research include the following:

1) Bacterial communities in high-elevation Sierra Nevada lakes exhibit predictable annual successional patterns linked to the timing and magnitude of snowmelt.

2) Phosphorus strongly limits the metabolism of bacteria in Sierran lakes, suggesting that continued depositional enrichment will alter rates of respiration and organic matter cycling in high-elevation catchments.

3) Bacteria change the composition of their communities in concert with seasonal changes in the source of organic matter in alpine lakes: from terrestrial runoff in spring to phytoplankton-derived organic matter in autumn.

4) The phylogenetic identities of bacteria in high-elevation lakes are similar throughout the world, with Sierran communities closely related to studies conducted in Crater Lake (USA), the Austrian Alps, and Hawaii.

Professional Presentations

Nelson, C.E., C.A. Carlson, J. O. Sickman, and J.M. Melack. Community composition and metabolism of high-elevation bacterioplankton linked to catchment inputs, landscape position, and seasonal limnological transitions. American Society of Limnology & Oceanography Summer Meeting, Victoria, British Columbia, Canada, June 4-9, 2006.

Collaborative Efforts

The interdisciplinary nature of this research has involved close collaboration with several research groups. Dr. Craig Carlson, a marine microbial ecologist at UCSB, has assisted with analyses of microbial parameters. Dr. James Sickman, a watershed biogeochemist at the University of Florida, has provided assistance with various analyses of organic matter composition. Drs. Roland Knapp and Orlando Sarnelle, respectively of the Sierra Nevada Aquatic Research Laboratory and Michigan State University, have provided access to and supporting data on lakes undergoing experimental fisheries manipulation.

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Quantifying Sediment Resuspension Linkages to Nutrient Enrichment in the Existing and Future Salton Sea

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The Salton Sea is a hyper-eutrophic water body characterized by low oxygen concentrations, massive fish kills, noxious odors and possibly related bird kills. Eutrophication in the Sea is driven primarily by nutrients associated with sediment resuspension. This research undertook a study at the Salton Sea to directly measure sediment resuspension. The measured data, in conjunction with existing UCD temperature instruments in the Sea and the CIMIS network, were analyzed for a relation between wind speed and turbidity, and will provide sufficient data to develop a new, process-based resuspension algorithm, and fully calibrate and validate it as part of the water quality model, DLM-WQ.

The Salton Sea is a terminal lake located in the southeastern desert of California, and is the largest "lake" in California. It occupies the northern part of the Salton Trough that includes the Coachella and Imperial Valleys of California and the Mexicali Valley of Mexico. Its main source of water is irrigation return water from the Coachella and Imperial Valleys' use of Colorado River water. Under the 2003 Colorado River Quantification Settlement Agreement and Salton Sea ecosystem restoration legislation, inflow to the Salton Sea is to be reduced by 20%, while at the same time part of the revenues raised by this historic transfer are to be used for the ecological restoration of the Salton Sea.

Currently the Salton Sea is a hyper-eutrophic water body characterized by low oxygen concentrations, massive fish kills, noxious odors and possibly related bird kills. Recent water quality modeling conducted by the University of California, Davis, indicated that eutrophication in the Sea is driven primarily by nutrients associated with sediment resuspension and suggests that inflow control alone will not produce the desired state. Sediment resuspension is a function of wind speed, water depth, lake fetch (resulting in wave development) and the density (thermal) stratification. As the Sea recedes (due to the 20% inflow reduction) or if, as appears possible, a massive construction project is undertaken to change the physical construction of the Sea, the extent

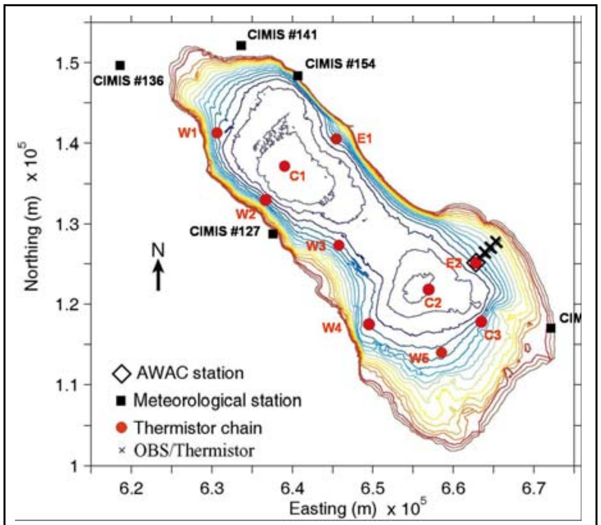

Figure 1. Map of the Salton Sea showing depth contours (at 1m intervals). Red circles are location of UCD thermistor chains. Black squares are locations of CIMIS meteorological stations. Crosses are the locations of the optical backscatter sensor stations.

and the effects of sediment resuspension will change.

This research undertook a 12 months study (including a four-month measurement program) at the Salton Sea to directly measure sediment resuspension using an array of optical backscatter sensors and a wave height and current profiling instrument. The data were provided by these instruments, in conjunction with existing UC Davis temperature instruments in the Sea and the CIMIS meteorological network (figure 1). The Sea was not strongly stratified for this research period, even though the surface of the Sea was weakly stratified. The time series data, including turbidity, wind speed, wave height and currents, were compared to one another to determine any relations among the measurements. The analysis of the time series reveals that the existence of a peak in wind intensity is associated with a peak in turbidity. These peaks of hourly wind speed seem to occur with quasi-invariant wave direction from the west. It also is interesting to see that important signal strengths are observed for day 252 – day 260 close to the bottom, which is compatible with wind speed at that period.

Based on the measured data, correlations between turbidity, which is assumed to be directly related with suspended solids in the water columns of the Sea, and wind speed are determined. These data also revealed that shear stress due to wave action was more dominant than that due to current. Non-linear relation between wind speed and turbidity were assumed and compared with other relations of sediment entrainment as a function of bed shear stress and the associated shear velocity.

In addition, sediment entrainment was calculated by two theoretical models, including Mian and Yanful (2004) for cohesive sediment and Garcia and Parker (1991, 1993) for non-cohesive sediment, and compared with measurements.

These two sediment entrainment models will be combined into the water quality model, DLM-WQ. The measured data fully calibrate and validate it.

The model can then be used to more fully explore the potential for ecological restoration of the Salton Sea, either under its present geometrical configuration or possible future configurations. The model, which is in the public domain, will also be applicable to many other lakes and reservoirs, where sediment resuspension or the nutrients and contaminants that are associated with the sediments, are an issue.

Professional Presentations

Schladow, S. G., Rueda, F. J., Fleenor, W. E. and Chung, E. G. Three-Dimensional Hydrodynamic Modeling of the Salton Sea. California Water and Environmental Modeling Forum Annual Conference, Asilomar, CA, 2006.

Collaborative Efforts

This research is providing input toward the ecological restoration the Salton Sea. This restoration is currently under investigation by the California Department of Water Resources and the US Bureau of Reclamation. We are working closely with staff from both these agencies, and their consultants. We are also collaborating with the USGS and NASA on Salton Sea related issues.

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Research Category III

Water Quality

Research in this category encompasses all aspects of water quality management. Topics include sources and the nature of contamination; effects of contamination on human health, plant and wildlife; wastewater treatment and reclamation processes; and retrospective evaluations of the effectiveness and impacts of different strategies utilized in California for improving water quality, in particular water reuse, and for preventing water quality degradation.

Development of Biosensor for Real-Time Analysis of Perchlorate in Water

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Perchlorate (ClO_4^-) contamination of ground water is a widespread problem in the U.S., which can adversely affect human health and wildlife. We report the development of a highly sensitive method for real time detection ClO_4^- detection in water.

Perchlorate (ClO_4^-) contamination of ground water is a widespread problem in the U.S., which can adversely affect human health and wildlife. Current methods for detecting and quantifying ClO_4^- in water are time consuming, expensive, and subject to error due to complex procedures and various interferences. Thus, there is an urgent need to develop a method that can accurately detect and measure low concentrations of ClO_4^- in the field.

We constructed and characterized a ClO_4^- biosensor for rapid determination of ClO_4^- in water by employing a ClO_4^- reductase from a novel perchlorate-reducing bacterium (*Dechloromonas* sp. perc1ace). Using a 3 mm glass carbon electrode (GCE), we successfully constructed a ClO_4^- sensing bio-electrode by coating an aliquot of the enzyme on the nafion (ion-exchange matrix) layer pre-coated on the polished surface of the GCE. Amperometric [i/t] measurements revealed linear increases in current in relation to time and ClO_4^- concentration. The biosensor responded strongly to ClO_4^- at concentrations as low as 1 μg/L and the sensor displayed a linear response to ClO_4^- concentrations in the range 25 to 100 μg/L. Response time to ClO_4^- at 100 μg/L was approximately 111 ± 28 seconds. Kinetic evaluation of the sensor response to ClO_4^- at 25 to 100 μg/L revealed a first order reaction ($r^2 > 99\%$) with k values of 10.3, 24.2, 33.9 and 48.2 at 25, 50, 75 and 100 μg/L, respectively. A strong linear correlation was established between biosensor response (nA) and ion-chromatography conductivity readings (μS) in the 25 to 100 μg/L linear domain of the biosensor. Biosensor response to ClO_4^- was maximal at applied potential range of –0.6 to –1.0V. ClO_4^- reduction current increased with increase in pH and was maximal in the range of 7.6 to 8.0. The ClO_4^- biosensor displayed excellent stability after repeated use (24 analyses conducted on day 1 over a 10-hour period at room temperature). Nitrate concentrations below the drinking water regulatory limit (<45 mg/L NO_3^-) did not interfere with ClO_4^- biosensor performance. This study indicates great potential for the development of a portable and field deployable biosensor for real time analysis of ClO_4^- in water.

Publications

Okeke, B. C., M. Guangyu, Q. Cheng, M. E. Losi and W. T. Frankenberger, Jr. (2006). Development of a Perchlorate Reductase Based Biosensor for Real Time Analysis of Perchlorate in Water. *J. Microbiol. Meth.* In Press (Available Online)

Okeke, B. C., M. Guangyu, Q. Cheng, M. E. Losi and W. T. Frankenberger, Jr. (2006). Perchlorate Detection in Water by a Microbial Enzyme-Based Biosensor.

Abstracts of the 106th General Meeting of the American Society for Microbiology, Orlando, FL.

Professional Presentations

Okeke B. C., Guangyu Ma, Quan Cheng, Mark E. Losi and William T. Frankenberger Jr. Perchlorate Detection in Water by a Microbial Enzyme-Based Biosensor. 106th General Meeting of the American Society for Microbiology, Orlando, FL, May 2006.

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Quantitative PCR Assays for Specific Host Sources of Fecal Pollution in Watersheds

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The purpose of this study is to develop and validate Quantitative PCR assays for host specific and reference targets and apply the assays to the San Pedro Creek Watershed in Pacifica, CA in order to identify sources of fecal pollution. Year 1 of the project has demonstrated significant methodology development and validation. In addition, sites in the San Pedro Creek Watershed with anticipated fecal pollution have been sampled, and over 96% contained elevated levels of fecal indicators, suggesting these sites significantly contribute toward watershed pollution. These samples are being processed for future analysis by QPCR.

The purpose of this study is to develop and validate quantitative polymerase chain reaction (QPCR) assays for host specific and reference targets and apply the assays to the San Pedro Creek Watershed in Pacifica, CA in order to identify sources of fecal pollution and focus remediation efforts.

Identifying the host sources of fecal pollution in watersheds is typically accomplished via microbial source tracking (MST), and is essential for effective remediation of watershed pollution. Host-specific microorganisms, which are found only or primarily in a single host species, are highly advantageous for MST. Since assays for host-specific microorganisms circumvent the need for the large host origin database that is required for most MST assays, they provide more specific, faster, and less expensive MST assays.

The San Pedro Creek Watershed in Pacifica, CA, is an important local recreational resource, provides steelhead rookery, and has both rural and urban aspects. The watershed also has elevated levels of fecal pollution that contribute to coastal pollution and beach closures.

San Pedro Creek Watershed sampling focused on areas suspected of contributing fecal pollution to the main stem of the creek, namely sites on the North Fork, above the Park Mall Shopping Center culvert (Figure 1, upper right corner - Big Bend area), and sites associated with tributaries that feed into the main stem from the South, primarily between Adobe and Highway 1 (Figure 1, lower left area).

Figure 1 San Pedro Creek Watershed

Four methods for isolation of genomic DNA were applied to a representative sampling of Enterococcus and E. coli cultures and evaluated by DNA yield from bacterial cultures, and by assay cost, overall time and technical time.

Significant progress has been made in the development and validation of QPCR assays for host-specific microorganism targets: (1) the esp gene of *Enterococcus faecium*, as a specific marker for human fecal pollution, and (2) two gene targets in *Enterococcus faecalis* as indicators for avian and human fecal pollution, plus two reference gene targets diagnostic for total *Enterococcus*, as indicators of total fecal pollution.

The QPCR assays were applied to fecal, sewage and environmental samples (Table 1). The human specific E. faecium target (Esp2b2) was positive for sewage and environmental samples with suspected human contamination, and did not react with avian, cow, dog, human or rabbit fecal samples. Furthermore, the human specific gene target identified 5 of 7 environmental samples with human fecal contamination (Table 2). All of the above data are fully consistent with the putative assay specificity, as the gene target is not found in all human individuals. The reference target (16Sb) reacted with all fecal, sewage and environmental samples, and exhibited similar levels of gene expression across all samples, confirming its efficacy as a reference marker for total Enterococci.

Table 1. QPCR Assays on Fecal, Sewage & Environmental Samples

Host	Human	Human/Avian	Total Entero
Gene	Esp2b2	Ace1a, Esp1a	16Sb
Positive	Sewage, Environmental	Bird, Cow, Dog, Human, Rabbit, Sewage, Environmental	Bird, Cow, Dog, Human, Rabbit, Sewage, Environmental
Negative	Bird, Cow, Dog, Human, Rabbit	None	None
Notes	>>250-fold differential	Lower Cts for non-target hosts	Similar Cts for all (20-21)

Blind environmental: Human contaminated watershed

Assays at 0.4 and 10 ng DNA/ul; CVs 0.5-2%

In summary, the first year of the project has demonstrated significant progress in assay development and validation, and methodology development. In addition, sites in the San Pedro Creek Watershed with anticipated fecal pollution have been sampled, and a high percentage (96.2%) of these watershed samples were found to contain elevated levels of fecal indicators.

Table 2. QPCR Assays on Environmental Samples with Human Fecal Contamination

Sample	Ct 16Sb	Ct ESP2b2	delta Ct
B1Sewage	20.3	34.6	14.3
B2Sewage	21.6	19.6	14.3
FDI DEL	18.3	29.7	11.4
HCSewage	19.6	33.8	14.2
Sewage20 10/26	18.0	>40	>21.98
Sewage3 10/26	19.3	>40	>20.67
Sluice	20.1	38.9	16.5

CVs (0.001-0.70)

Final results of this study are anticipated to facilitate the identification of sources of fecal pollution in watersheds, and thus enable more efficient watershed management. In particular, the focus on development of assays for human fecal pollution will impact the sources of pollution from which humans experience the highest health risk.

Publications

Ivanetich, Kathryn, Pei-Hsin Hsu, Kathleen M. Wunderlich, Evan V. Messenger, Ward G. Walkup IV, Troy M. Scott, Jerzy Lukasik, Jerry Davis, Microbial Source Tracking by DNA Sequence Analysis of the *Escherichia coli* malate dehydrogenase gene. *Journal of Microbiological Methods* 67, 507-526 (2006).

Professional Presentations

Ivanetich, Kathryn, Status of California Watersheds and Novel Methods to Identify Host Sources of Fecal Pollution, California State University at Chico, Department of Chemistry and Biochemistry, April 2006.

Collaborative Efforts

Troy Scott, Ph.D., and George Lukasik, Ph.D., Biological Consulting Services of North Florida, and University of Florida, Dept. of Microbiology and Cell Science, Gainesville, FL.

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A Quantitative Detection Method for Host-Specific Fecal Bacteria Based on Real-Time, qPCR

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A major challenge to quantifying E. coli *using quantitative polymerase chain reaction (qPCR) is that the PCR reagents themselves are contaminated with* E.coli *DNA. In this project we developed a pretreatment step to eliminate the contaminant DNA, which allowed us to detect a single* E.coli *cell using qPCR.*

Current detection methods and monitoring approaches are inadequate for developing successful and cost-effective strategies for reducing fecal pollution. One of the main limitations of the current culture-based detection methods is that they do not distinguish between bacteria that originate from different hosts, such as a human, cow or bird. Because any particular water (e.g., lake, river, estuary, or beach) is likely to receive pollution from multiple point and non-point sources, the inability to distinguish host-specific indicators significantly limits the ability to identify and target the main sources, placing a major constraint on the management of fecal pollution. A variety of new approaches that exploit host-specific fecal bacteria to conduct microbial source tracking (MST) studies are being explored. While many of the methods may eventually provide powerful tools for identifying the wide range of human and animal point and non-point sources that contribute fecal pollution to a water body, none of the molecular methods currently has the potential to provide a direct quantitative measure of the fractional contribution from each of the sources to the total concentration of fecal pollution.

Quantitative methods are needed to identify and target the dominant sources of pollution, to monitor changes in the concentration of fecal pollution and its sources over time, to assess the effectiveness of specific mitigation strategies, and to provide more information for evaluating the true public health risks. Therefore, the goal of our research is to develop a quantitative method for calculating the fractional contribution of fecal pollution from human and animal sources by measuring host-specific fecal indicator bacteria using real-time, quantitative polymerase chain reaction (qPCR).

E.coli is the most common fecal indicator organism for water quality assessment, yet a major impediment to the use of qPCR for detection of *E.coli* is that the PCR reagents themselves are contaminated with *E.coli* DNA. This contamination makes it impossible to measure low concentrations of *E.coli* in a water sample, which severely limits the utility of *E.coli* qPCR for environmental applications. Therefore, the major thrust of our research has been developing and validating a method to eliminate the contaminant DNA prior to qPCR. We successfully developed and compared two decontamination methods, one using an enzyme to degrade the DNA (DNase), and the other using ultrafiltration to physically remove the contaminant DNA. These decontamination methods will be useful beyond our specific application, as many researchers and microbiologists work on qPCR applications that suffer from DNA reagent contamination. We then combined the decontamination methods with qPCR to develop a robust enumeration method for *E.coli*.

The next step in our project is to use our new qPCR method for *E.coli* along with similar methods that have been developed for other fecal indicator organisms as well as host-specific fecal bacteria. We will use these methods alongside traditional culture-based methods to understand what fraction of total fecal bacteria is contributed by each sub-group of bacteria in both human and animal fecal sources. This information is essential before the fractional contribution of different fecal sources can be determined. In addition, we are using these new qPCR methods to help identify the key pollution sources in Rodeo Lagoon, as described in the section below.

Professional Presentations

K.L. Nelson, "Real-time, quantitative, PCR detection of *E.coli* and *Ascaris* eggs." International Symposium on Waterborne Pathogens, Athens, GA March 16-18, 2006.

Collaborative Efforts

The support of UCCWR has resulted in several new collaborations. This fall we will apply the methods developed in our project to a new field site in the Golden Gate National Recreation Area, Marin County, CA. In collaboration with Prof. Mark Stacey (CEE, UC Berkeley), the project aims to identify sources of nutrient pollution in Rodeo Lagoon, which suffers from annual toxic blue-green algae blooms and fish kills, including the endangered tidewater goby. A grant from the National Park Service is supporting this research. We have also initiated a second collaboration with Prof. Kate Field at Oregon State University and Prof. Stefan Wuertz at UC Davis, who are both leaders in the development of quantitative, molecular methods for fecal source tracking. This research will help us understand how new molecular methods compare with traditional methods for measuring fecal bacterial contamination from human and animal fecal sources.

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Do Constructed Flow-Through Wetlands Improve Water Quality in the San Joaquin River?

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In the Central Valley, constructed wetlands can improve water quality of irrigation return flows by intercepting and/or transforming particulate organic carbon, nitrogen, phosphorous and sediment before it reaches the San Joaquin River.

The primary goal of this study is to evaluate the efficacy of using constructed wetlands (CW) to improve water quality in irrigation return flows ultimately destined for the San Joaquin River. Two CWs were monitored during the 2005 irrigation season (April - Sept.), a new CW (W-1) and 12-year-old CW (W-2). No monitoring occurred in 2006 due to flood conditions that remained until August.

Sediment samples were analyzed for carbon, nitrogen, phosphorus and particle size; and intricate input/output flow monitoring systems were installed to calculate constituent loads. Input/output waters from CWs were collected on a weekly basis and analyzed for: total nitrogen (TN), total phosphorus (TP), dissolved organic carbon (DOC), particulate organic carbon (POC), total suspended solids (TSS), volatile suspended solids (VSS), and chlorophyll-a (a measure of algal biomass). High frequency sampling with autosamplers was also employed to better understand the temporal variability in water quality constituents. Carbon, nutrient and sediment retention efficiency was evaluated from input/output concentration data.

Particular emphasis was directed toward phosphorus cycling in 2005-2006. Suspended solids from input and output waters were processed through a sequential phosphorus extraction procedure in order to characterize the different P fractions.

Results

The work has enabled us to compare the older CW with the newly constructed CW, but differences in size and irrigation water received may have complicated the results. Both CWs are clearly effective at capturing sediment and nutrients discharged from irrigated farmland.

Constructed wetlands have a potential to store carbon. After receiving tail water over the 2004 and 2005 irrigation seasons, the average soil organic carbon content of seasonally submerged soils increased almost five-fold at W-1 and approximately ten-fold at W-2.

In samples from 2004, chlorophyll-a tended to be higher in water at W-1 compared to W-2, especially at the input. In 2005, W-2 became a source of chlorophyll-a, while W-1 showed no differences between input and output. During spring 2005, CW-2 was not allowed to dry out. This prevented the germination of emergent vegetation, which allowed more light into the system over the irrigation season resulting in more algae.

While W-1 was generally a sink for DOC in 2004, W-2 was often a source, possibly due to leaching of DOC from vegetation and litter. In 2005, W-1 was a sink for DOC over 70% of the irrigation season; W-2 was a source roughly 50% of the season. A comparison of concentration and load data for DOC at input and output locations illustrates that although the concentration of DOC was greater at the outputs, the actual amount of DOC exiting the CW as a load was much less than what entered. This was true at W-1 and to a lesser extent at W-2.

Both wetlands were effective in reducing bio-available phosphorus (BAP) throughout the season. Dissolved phosphorus (DP) removal was high in both wetlands although the average removal efficiency was higher in the older, larger CW than in the newer, smaller one. Removal efficiencies for particulate P were similar.

The retention of particle bound P is considered one of the primary retention mechanisms of constructed wetlands. Total suspended solids were significantly lower in both wetlands at the outputs relative to the inputs. This retention of suspended solids occurs primarily from the settling of particles due to decreased water velocities. As water flows through the wetlands and larger particles are deposited, the proportion of fine textured solids reaching the output increases.

Publications

O'Geen, A.T., J.J. Maynard, and R.A. Dahlgren. Efficacy of constructed wetlands to mitigate non-point source pollution from irrigation tailwaters in the San Joaquin Valley California, *USA Water Science and Technology*, In press.

Professional Presentations

Maynard, J.J., A.T. O'Geen and R.A. Dahlgren, Using Constructed Wetlands to Remove Water Quality Contaminants in Agricultural Return Flows. California Plant and Soil Science Conference, Modesto CA, Feb. 2005.

O'Geen Preliminary water quality monitoring in constructed wetlands. San Joaquin River Management Program Advisory Council, Modesto, Mar. 2005.

O'Geen, A.T., J.J. Maynard and R.A. Dahlgren, Strategies for Attenuating Hypoxia in the Lower San Joaquin River, California, World Water & Environmental Resources Congress, Anchorage AK, May 2005.

Maynard, J.J., A.T. O'Geen and R.A. Dahlgren, A Spatial Investigation of Bio-Available Phosphorus in Submerged Wetland Soils, Western Society of Soil Science Annual Meetings, Ashland OR, Jun. 2005.

Brauer, N, A.T. O'Geen, J.J. Maynard, and R.A. Dahlgren, Mineralogical Characterization of Seasonally Submerged Wetland Soils Western Society of Soil Science Annual Meetings, Ashland, OR, Jun. 2005.

O'Geen, A.T., Efficacy of constructed wetlands to mitigate non-point source pollution in the San Joaquin Valley California USA, Diffuse Pollution Specialist Conference, Johannesburg, South Africa, Aug. 2005.

O'Geen, A.T. and R.A. Dahlgren. Field tour for the Southwest States and Pacific Islands Regional Water Quality Program. Jun. 2006.

Maynard, J.J., A.T. O'Geen and R.A. Dahlgren, Transformations of Biologically-labile Particulate Phosphorus in Constructed Wetlands, Western Society of Soil Science Annual Meetings, Park City UT, Jun. 2006.

Maynard, J.J., A.T. O'Geen and R.A. Dahlgren, Effects of sedimentation on phosphorus retention in seasonally submerged wetland soils. World Congress of Soil Science, Philadelphia, PA. Jul. 2006.

Collaborative Efforts

This project has fostered collaborations with the USDA-NRCS District Conservationist in Stanislaus County, Fish and Wildlife Service, Bureau of Reclamation, and the State Water Resource Control Board.

This project has also initiated a collaborative effort with the San Joaquin River Wild Life Refuge, one of the largest holdings of natural and constructed wetlands in the Central Valley.

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Identification of Viable Cells of *E. coli* O157:H7 in Environmental Waters using Quantitative PCR

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In the development of a microarray to identify pathogens, several preliminary points became evident. These were interference reducing the accuracy of quantification; viability; and effect of matrix on standard curves.

Under the Clean Water Act, Total Maximum Daily Load requirements for fecal coliforms established by the US EPA and its state representatives are proving difficult to meet. Agencies and cities in charge of runoff from storm drains and other discharge points into environmental waters are investing large amounts of public funds to identify and control fecal sources. To aid water managers in identifying waste quickly and inexpensively, we propose to develop an oligonucleotide microarray that will identify four fecal waste sources (human, cow, pig and bird) and a major bacterial pathogen, *E. coli* O157:H7, simultaneously with results available within 48 hours.

In the development of a microarray to identify pathogens, several preliminary points became evident. These were interference resulting in a reduction of the accuracy of quantification; viability; and effect of matrix on standard curves. We have optimized a compound of bovine serum albumin for direct DNA extraction from sewage sludge, sediments, activated sludge, stream waters and raw sewage to remove interference in quantitative polymerase chain reaction (PCR). Additionally, if no interfering compound is present, this compound does not reduce the sensitivity of the assay. A DNA intercalating compound has been developed that can be used to develop a viability assay that can accompany any quantitative PCR assay prior to DNA extraction. This addition to quantitative PCR testing means that for public health purposes viability can be incorporated into the assay.

To date, we focused on *Escherichia coli* O157:H7 because this organism is an important human pathogen that has been attributed as the primary cause of hemolytic uremic syndrome and hemorrhagic colitis in the United States. Many of the estimated 73,000 cases of *E. coli* O157:H7 infections have been a result of exposure to contaminated recreational waters or consuming contaminated drinking water or food, especially ground beef.

Our overall approach is based on quantitative PCR using dual labeled probes that would allow investigators to capture multiple genetic markers specific for a target pathogen from a complex matrix, as explained for *E. coli* O157:H7. This method promotes maximum flexibility because assays could be tailored to sample specific concerns. Molecular methods such as conventional quantitative PCR lack the ability to determine cell viability, but additional techniques may be employed to circumvent this obstacle. We adopted a method based on treating our samples with a nucleic acid stain that would prevent PCR amplification of nonviable cells. Therefore, if we observed quantitative amplification of our designated targets, we could be certain these are from live cells. This analysis provides a more accurate microbial description of our sample. Our viability assay was screened and optimized using pure cultures while the environmental samples consisted of secondary effluent, cow feces, and cow waste lagoon waters.

Including the cell viability analysis appears to be very promising. Figure 1 indicates a 4 log reduction using quantitative PCR for the *fli*C gene of *E.coli* O157:H7 when treated with optimal nucleic stain concentrations. We have observed this compound to inhibit bacterial growth as shown by figure 2, but quantitative PCR is still able to detect the entire bacterial population prior to treatment with the nucleic stain. Additionally, in dealing with interference due to the environmental matrix we have included bovine serum albumin. This substance increased detection in the presence of interfering compounds and produced no ill effects in the absence of interference.

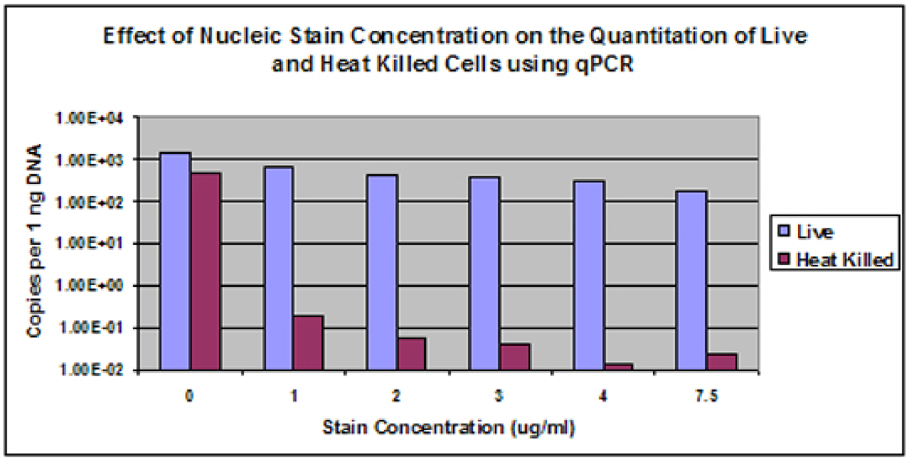

Figure 1.

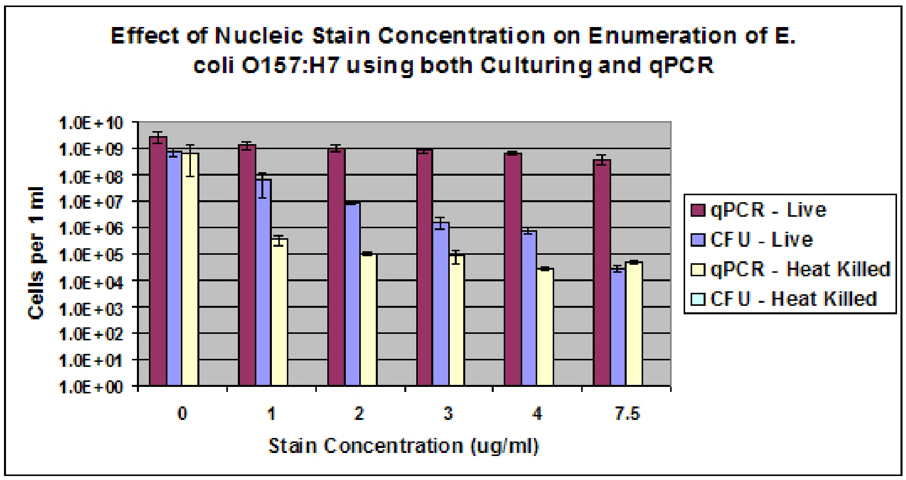

Figure 2.

This research is important to water quality because *E. coli* O157:H7, as well as other pathogens, continue to pose a threat to public health regardless of the improved safety measures required by regulation agencies. This research method is robust in that it successfully deals with interference and cell viability. Our research will present a simple and efficient method to identify viable pathogens in the environment. As a tool it is important because it provides an accurate description of the microbial population from any given source.

Professional Presentations

Phil Gedalanga and Betty H. Olson, Identification of *Escherichia coli* O157:H7 Specific Genes *fli*C and *stx*1 in Environmental Matrices Using Quantitative PCR Coupled with Magnetic Capture Hybridization, American Society for Microbiology, Orlando, FL, May 2006.

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Impacts of Ethanol on Anaerobic Production of Tert-Butyl Alcohol (TBA) from MTBE in Groundwater

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Tertiary butyl alcohol (TBA) is an undesirable byproduct of methyl tertiary butyl ether (MTBE) biodegradation. Ethanol, which is increasingly being used as a gasoline oxygenate, appears to stimulate formation and reduce removal of TBA in groundwater.

Tert-butyl alcohol (TBA), a toxic and possibly carcinogenic substance, is an emerging environmental contaminant. There is mounting evidence that TBA is being produced from a remnant chemical in most sub-surface plumes of leaked gasoline: methyl tert-butyl ether (MTBE). MTBE usage as a gasoline oxygenate and octane enhancer is decreasing due to regulatory changes. However, it appears that ethanol, which is replacing MTBE in gasoline reformulations, promotes MTBE conversion to TBA, most likely via a microbially mediated process. Our group aims to elucidate the geochemistry of MTBE transformation in gasoline plumes and the role of microorganisms in this process.

Our field-site at the Vandenberg Air Force Base, in Lompoc, California, was originally the site of a leaking underground storage tank. The area has been characterized by our group using a dense network of monitoring wells. We compared the impact of releasing gasoline constituents benzene, toluene and xylene (BTX), with and without ethanol to evaluate its impact on existing MTBE contamination. To validate these results, controlled release of MTBE was also carried out.

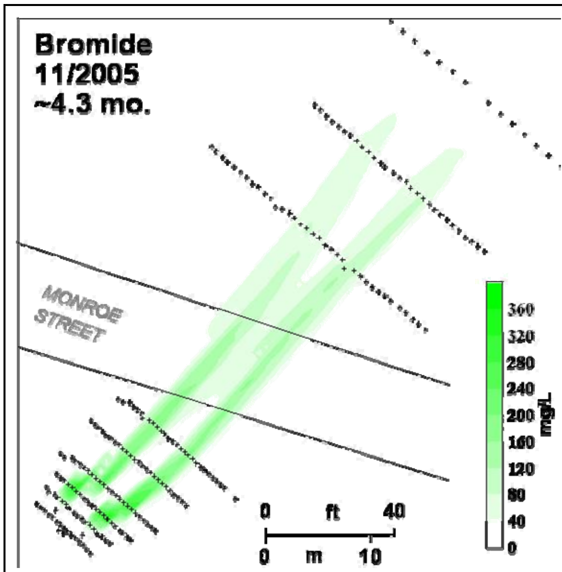
Our results indicate that ethanol reduces the degradation of BTX and enhances conversion of MTBE to TBA. We collected numerous samples along different transects and time points to monitor changes in the microbial communities and populations. We are using three methods to monitor micro-organisms: qualitative fingerprints of total bacteria and archaea using terminal fragment length polymorphism (TRFLP) analysis; quantitative polymerase chain reaction (PCR) to monitor abundance of both archaea and bacteria; and denaturing gradient gel electrophoresis (DGGE) combined with sequencing to identify dominant members of the community.

Alongside the field studies, microcosm studies are currently being carried out to investigate anaerobic MTBE conversion under controlled conditions. Microcosms using sediment and groundwater from the field site were set up to answer the questions: 1) What is the mechanism of anaerobic conversion of MTBE to TBA? 2) Can TBA be degraded under sulfate-reducing conditions present at the site? Concentrations of TBA and MTBE are measured over time, to determine whether

Graduate student Irina Chakraborty preparing microcosms in an anaerobic glove box.

degradation or conversion is occurring at all, and samples are collected over time for microbiological analysis. The microcosm studies also provide an opportunity to isolate microorganisms of interest in pure culture, allowing detailed study of their physiology. Similar work carried out by our lab on an aerobic MTBE degrader, *Methylibium petroleiphilum*, has yielded a wealth of information on the degradation of MTBE in oxygenated environments, and has led to the development of novel treatment approaches.

To understand the biodegradation in the field, it is essential to characterize the geo-chemical processes at the site by physical and chemical analysis of groundwater and sediment material. We released a solution of bromide, which acts as an unreactive tracer in this environment, to delineate the flow path of groundwater. Bromide tracer was monitored over time to determine the velocity of groundwater flow, and to account for seasonal variations. Measuring the properties of the sediment and the contaminants (e.g. porosity, sorption of contaminant to the sediment, hydraulic con-ductivity), permits separation of microbial degradation from the physical processes that lead to reduction in contaminant concentrations. We are currently modeling both processes using an environmental fate and transport model, HYDROGEOCHEM 5.0. By understanding the environmental triggers of the conversion of MTBE to TBA, optimal remediation approaches can be developed.



Bromide tracer data shows little lateral dispersion of groundwater at Site 60 at the Vandenberg AFB, as seen by the formation of two distinct lanes. Such conditions are ideal for controlled release experiments.

Publications

MacKay, D., N. de Sieyes, M. Einarons, K. Feris, A. Pappas, I. Wood, L. Jacobson, L. Justice, M. Noske, K. Scow and J. Wilson. Impact of Ethanol on the Natural Attenuation of Benzene, Toluene, and o-Xylene in a Normally Sulfate-Reducing Aquifer, *Environmental Science & Technology,* ASAP Web Release Date: 9/1/2006.

Nakatsu, CH; K. Hristova, S. Hanada, X.-Y. Meng, J.R. Hanson, K.M. Scow and Y. Kamagata. 2006. *Methylibium petroleiphilum* gen. nov., sp. nov., a novel methyl tert-butyl ether-degrading methylotroph of the *Beta-proteobacteria. Int J Syst Evol Microbiol 56: 983-989.*

Professional Presentations

Irina Chakraborty, Karen Andrade, Kevin Feris, Nicholas de Sieyes, Doug MacKay and Kate Scow. Formation and fate of tert-butyl alcohol in anaerobic environments, Superfund Basic Research Program Annual Meeting, New York, January 2006.

Collaborative Efforts

Prof. Tim Ginn from the Civil & Environmental Engineering Department at UC Davis. Jennifer MacKelvie, graduate student at the Univ. of Toronto. Nicholas de Sieyes, graduate student at Stanford University. Prof. Kerry Sublette of the Univ. of Tulsa.

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Diuron in California's Water Supply: Transformations and Associated Risks

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Diuron is the third most commonly used herbicide in California, and nearly all applications coincide with California's rainy season. Because diuron is moderately persistent in the environment, detection of the compound in California water supplies is common. Chlorination or chloramination of diuron, or similar compounds, during water disinfection has been shown to produce the potent carcinogen N-nitrosodimethylamine (NDMA). This project seeks to: (1) determine the rate and extent of toxic byproduct formation during chlorination or chloramination of diuron containing waters, and (2) assess the range of likely human exposures to these byproducts. Work in this first year confirmed that significant quantities of NDMA could be produced under some test conditions; actual human exposures, if any, remain unclear.

Diuron is the third most commonly used herbicide in California (over 1.5 million pounds annual usage in 2005). Nearly all applications (95%) are in late fall through early spring, which coincides with California's rainy season. Spot surface water monitoring, conducted by the Department of Pesticide Regulation between 1992 and 2002, frequently detected the presence of diuron. Monitoring of various organic compounds two or three times a year by the Department of Water Resources for the state water project has also resulted in frequent detection of diuron.

The primary reason for concern about diuron in source waters is the chance of forming carcinogens, such as N-nitroso-dimethylamine (NDMA), from diuron directly or from its breakdown product, dimethyl-amine (DMA). In addition, the formation of other byproducts, such as chlorinated anilines, may also impart unacceptable risks.

The objectives of the project are to: 1) determine the kinetics of toxic byproduct formation during chlorination or chlor-amination of diuron containing waters from the California Aqueduct; and 2) assess, through a combination of field sampling and modeling, the range of human exposure to diuron's byproducts via treated waters derived from the California Aqueduct.

The first phase of the project has been to test the potential for NDMA formation during chlorination of diuron. The results acquired support the hypothesis that appreciable amount of NDMA can be produced from the chlorination of diuron (Figure 1). Similar experiments were also conducted to investigate the effects of different initial diuron concentrations and pH values.

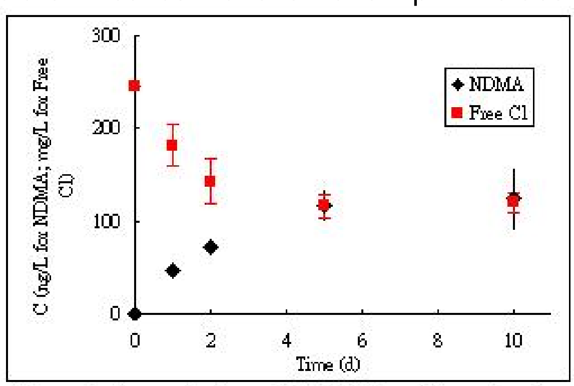

***Figure 1:** Concentration of NDMA (♦, ng/L) produced in the diuron chlorination study, and of free chlorine as Cl_2 (■, mg/L) at the end of reaction (The initial diuron concentration is 20 mg/l, and pH = 8). The point and bar represent the mean value and one standard deviation, respectively.*

Results indicate that lower concentrations of diuron produced lower concentrations of NDMA at the end of experiments (Figure 2), and the optimal pH range of NDMA formation from diuron is 6 to 10, which is similar to the proposed optimal pH range of NDMA formation from DMA (Figure 3).

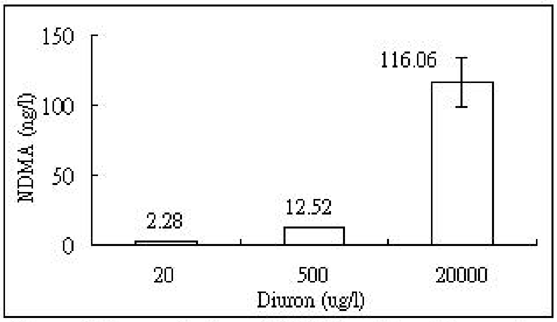

Figure 2: Concentration of NDMA produced in samples containing various initial diuron concentrations after 5 days (pH = 8). The number and bar represent the mean value and one standard deviation, respectively.

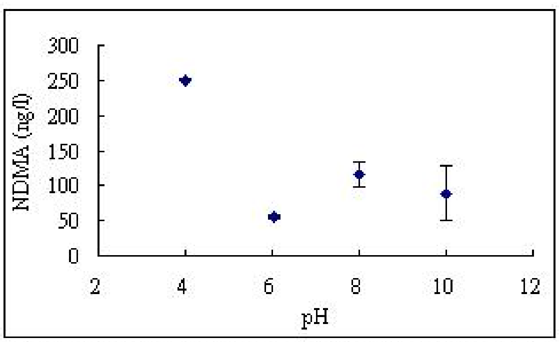

Figure 3: Concentration of NDMA produced in samples containing various pH values after 5 days (The initial diuron concentration is 20 mg/l; acetate buffer for pH 2, phosphate buffer for pH 6 and 8, carbonate buffer for pH 10). The point and bar represent the mean value and one standard deviation, respectively.

Work during the next year of the project will clarify the formation kinetics of NDMA and other toxic byproducts during chlorination and chloramination of diuron, which is essential to determine the risk posed by diuron in any location where it is a contaminant of concern. Estimates of human exposure to diuron and its byproducts in drinking water will allow identification of specific regions in the California Aqueduct, if any, where the treatment plants should be modified.

Professional Presentations

Wei-Hsiang Chen, Peter Green, and Thomas Young, Diuron in California's water Supply: Transformation and Associated Risks, California-Nevada Section, American Water Works Association, Reno, NV, August 2005.

Wei-Hsiang Chen, Peter Green, and Thomas Young, Diuron in California's Water Supply: Transformation and Associated Risks, UC Water Resources Coordinating Conference and Surface Water Quality Workshop, Woodland, CA, April 2006.

Wei-Hsiang Chen, Peter Green, and Thomas Young, Diuron in California's Water Supply: Transformation and Associated Risks, The Future of Agriculture: Science, Stewardship, and Sustainability, International Conference, Sacramento, CA, August 2006.

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Research Category IV

Water Development and Management Alternatives

This category encompasses economic and systems analyses approaches for formulating and evaluating water resources planning, development and management alternatives. Topics include policies and programs directed at increased water savings and water reuse; development of models for use in planning and operating water supply systems; conjunctive use of surface and subsurface storage; water markets and water pricing; and development and improved criteria for water project planning.

Imperial Valley Agriculture and Water: A Regional Economic Analysis

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We are in the final stages of this project with results currently being generated investigating a wide variety of policy scenarios. Results will provide information on the impacts of these policies on agricultural production, drainage water generation (which is important to the inflows to the Salton Sea), agricultural labor, income, and water demand. These results can then subsequently be fed into the SAM model to get an estimate of the regional effects on income and labor.

The objective of this research is to evaluate issues associated with potential reductions in the quantity or quality of drainage water entering the Salton Sea from agriculture in the Imperial Valley. This evaluation will be done by building a regional agricultural production model that accurately represents regional cropping activities, irrigation choices, and water issues. By developing a detailed regional mathematical programming model of Imperial Valley agricultural production, we can evaluate the impacts associated with alternative strategies that meet these commitments on agricultural productivity and sustainability. Furthermore, by linking this agricultural production model to a comprehensive regional model of economic activity (using what is referred to as social accounting matrix multiplier analysis, or SAM), the impacts on regional economic activity can also be explored and highlighted. Given that agriculture is the largest industry within the region, including the impacts of alternative agricultural management strategies on the region as a whole can provide a more comprehensive analysis than agricultural production models alone, and can better identify more efficient alternatives and their distributional consequences. Finally, through establishing a relationship between agricultural runoff from the Valley and inflows into the Salton Sea, the implications of these various strategies on characteristics of the Salton Sea can be explored.

The regional agricultural model is up and running. The model can estimate the regional agricultural impacts of different constraints on the input of water, restriction on irrigation efficiency, and the introduction of a water market (transfer) to the San Diego County Water Control Board. The outputs from this model, income, agricultural profits, and labor, can be input to the SAM to investigate the regional impacts on regional employment, income, and tax revenue in the aggregate or by industry.

We are finishing up validating the results of the base model with what we observe currently in the Imperial Valley. We have finished some sensitivity analysis of the model to ensure that the results correspond with economic theory. That is, when you increase the price of irrigation water, the model responds in the correct direction and magnitude.

We are currently working to ensure that we have a very complete grasp of the policy options confronting the Imperial Irrigation District and the State of California regarding the water transfer under the Quantification Settlement Agreement. The transfer consists of commitments associated with water conservation measures, water transfers, and groundwater banking and conjunctive use measures. The state of California was given 15 years to achieve these commitments, many of which rely upon agricultural growers in the region reducing their long-term historical average water use by nearly 30% (Western Water 2001, p. 8), and one that includes a controversial 200,000 ac-ft transfer of water from the Imperial Irrigation District to the San Diego County Water Authority. Once we fully grasp the relative magnitudes of the transfers and options, we incorporate these into our model and compare the results with our baseline solution, as well as with what would be likely be called the economically efficient solution. For instance, as the plan stands currently, water from IID that can be sold to San Diego County may come from water savings from growers through fallowing crop land. Yet, a potentially more efficient solution might be, or include, some water reduction strategies through either reducing the amount water growers apply by increasing the irrigation efficiency of water applications, or through changing the crop mix that they cultivate. These strategies can be compared to what is currently being mandated by the authorities.

In summary, we are in the final stages of this project. Results are currently being generated investigating a wide variety of policy scenarios. The results will provide information on the impacts of these policies on agricultural production, drainage water generation (which is important to the inflows to the Salton Sea), agricultural labor, income, and water demand. These results can then subsequently be fed into the SAM model to get an estimate of the regional effects on income and labor.

Collaborative Efforts

We have been in direct contact with the Salton Sea Authority about investigating the impacts of the QSA on the viability of the Salton Sea Restoration alternatives and the benefits and costs of those alternative strategies. Clearly, to completely understand the benefits and costs of any restoration strategy, such an economic exercise needs to be performed. Hence, we will make our results available to this agency.

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Futures Markets for Water in California: Effective Management of Supply-Side Risk

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We seek to determine the theoretical value of transferring water uncertainty from one party to another at several locations in California, given current water prices and the spatial and temporal distribution of water year types in the state. Our simulation-optimization model currently makes the calculation for the northernmost region of California; next, we plan to extend the model to the rest of the State.

In California, the tremendous spatial and temporal variation in precipitation suggests that flexible contractual arrangements, such as option contracts, would increase allocative efficiency of water over time and space. Under such arrangements, a water agency pays an option premium for the right to purchase water at some point in the future, if water conditions turn out to be dry. The premium represents the value of the flexibility gained by the buyer from post-poning its decision whether to purchase water. In California, the seller of existing option arrangements is often an agricultural producer who can fallow land, in the event that a water option is exercised.

In this analysis we seek to determine the theoretical value of transferring water uncertainty from one party to another at several locations in California, given current water prices and the spatial and temporal distribution of water year types in the state. (Preliminary analysis covers northern California; future analysis will incorporate southern California.) We use tools from finance theory and output from CALVIN, an economic-engineering optimization model of the California water system. CALVIN runs the current configuration of the California water system over historical hydrological conditions, to generate water's imputed price at different locations during different seasons. We analyze within a mathematical programming framework whether increased trading among water agencies across time as well as space would result in significant gains from trade. Finally, we explore reasons why previous theoretical calcula-tions of option value in the western United States have far exceeded option premia on existing bilateral contracts.

Professional Presentations

Hansen, Kristiana, Richard Howitt and Jeffrey Williams, Water Options in California: Effective Management of Supply-Side Risk, American Agricultural Economics Association, Long Beach, CA, July 2006; and Universities Consortium on Water Research, July 2006.

Collaborative Efforts

Economists at the Bureau of Reclamation, Lower Colorado Division in Boulder City, Nevada, have expressed significant interest in the final outcome of this project and continue to provide guidance and sug-gestions on the modeling of institutions within the project.

This simulation-optimization modeling pro-ject and the difficulties associated with acquiring data on water transfers due to the infrequency of trades and the reluctance of water traders to provide such information have led us to explore another avenue of research. We have begun an experimental economics project to examine the behavior of subjects under different market institutions in a laboratory setting. This research is undertaken with colleagues in the Department of Economics at Sacramento State University, Jonathan Kaplan and Stephan Kroll.

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Model Development for Conjunctive Use Planning and Aquifer Protection in Semi-arid Regions

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The goal of this research is to develop a decision support system (DSS) for sustainable groundwater management, including conjunctive use planning of surface water and groundwater, and aquifer protection. The proposed DSS will encompass a management framework that links simulation to optimization.

In the semi-arid region of the Southwestern United States, population and economic growth are making increasing demands on the water supply. For example, almost 40% of the water supply in Southern California is from groundwater. To protect groundwater from over-pumping and contamination, there is a critical need to develop surface water and groundwater management tools that can be used to predict water level variations and solute concentrations in the aquifer under different management scenarios. By controlling the total water resources of a region, conjunctive use planning can increase the efficiency, reliability, and cost-effectiveness of water use, particularly in river basins with spatial and temporal imbalances in water demand and natural supplies.

Typical of Southern California, the Warren Basin, located in San Bernardino County, has seen sustained population growth and increased water demands since the 1950's. Since groundwater is the only local source of water supply available, water levels experienced a steady decline of up to 300 ft in some areas between 1956 and 1994. In 1995, the Hi-Desert Water District (HDWD) implemented a recharge program using imported State Water Project (SWP) water and two recharge pond sites. As a consequence, water levels rose up to 200 ft in some areas. However, nitrate concentrations increased drastically, from a baseline level of approximately 10 mg/L to values in excess of 100 mg/L. A study conducted by the USGS showed that the increase in nitrate concentrations is due to entrainment of seepage from septic tanks and irrigation, previously stored in the unsaturated zone, by the artificially elevated water table.

The goal of this research is to develop a decision support system (DSS) for sustainable groundwater management, including conjunctive use planning of surface water and groundwater, and aquifer protection. The proposed DSS will encompass a management framework that links simulation to optimization. We will use the geological information and historical data collected by the USGS for the Warren Basin for the development of the simulation model. The developed simulation model will be linked to an optimization model for conjunctive use planning and aquifer protection. Additionally, we will develop algorithms for parameter structure identification, model reliability analysis, data sufficiency evaluation and monitoring network design.

Currently, we have completed the development and calibration of a flow and transport simulation model for the Warren Basin. Geological information for the Basin, and historical water level and nitrate concentration observations are provided by the Water Resources Division of the USGS.

Collaborative Efforts

Arrangements have been made with Dr. Tracy Nishikawa of the USGS office in San Diego for collaborative participation in the project.

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Research Category V

Water Law, Institutions and Policy

This category encompasses all institutional frameworks (policies, laws, administrative processes, and regulations) for developing and managing water resources. Topics include institutional management of water scarcity and ground water; taxes, fees and user charges for watershed management or related objectives; potential institutional conflicts associated with specific water development and management alternatives; and the evolution of water management institutions in California. Policy studies which involve analytical investigations of alternative polities for managing California's limited water resources are also encouraged in this category.

An Economic Analysis of Groundwater Nitrate Pollution Control in Dairy-Intensive Watersheds

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This project develops a mathematical programming model for assessing the economic costs and environmental effects of groundwater nitrate pollution control strategies in dairy-intensive watersheds.

This project develops a mathematical programming model for assessing the economic costs and environmental effects of groundwater nitrate pollution control strategies in dairy-intensive watersheds. The programming model is an optimization model that derives the anticipated response of a farmer to a given set of operating conditions. This allows us to predict the effects of nitrogen regulations on farm production, farm income, and waste emissions. The model includes components for farm-level decision-making, herd and crop production, waste generation and reuse, and nitrogen emissions to the environment.

Previous work on nutrient pollution from animal feeding operations relies on models that greatly simplify the farm management problem. For example, temporal aspects of the problem are not addressed and the possibility of shifting pollution from one environmental medium to another is not considered. These simplifications can lead to prediction errors in pollution control policy simulations. Therefore we propose a much more detailed farm-level model that gives explicit treatment to temporal aspects of the farm management problem and allows for cross-media pollution effects, among other innovations.

Three sources of temporal effects are incorporated into the model. First, the dynamic nature of managing a dairy herd implies a farmer's optimal response to changing operating conditions will not necessarily be instantaneous. Rather, there may be a gradual transition from one herd profile to another. Second, dairies apply organic nitrogen which must be mineralized before it can be leached. And third, nitrogen emission rates depend on the stock of soil nitrogen which evolves through time. We also allow for modifications to the waste handling system that control how much waste nitrogen is emitted as nitrate to groundwater and as ammonia to the atmosphere.

Our findings are summarized as follows. The estimated cost to implement an effective nutrient management plan is at least twice as high as previous estimates, owing to both differences in model structure and farm characteristics. We find that in addition to off-site hauling of waste, shifting emissions from nitrate to ammonia is an important response by farmers when cross-media regulations are not implemented; and herd reductions are an important response when such regulations are implemented. With regard to temporal effects, we find that although initial reductions in nitrate leaching occur quickly, new steady state levels are not achieved for approximately 7 to 9 years.

Professional Presentations

Baerenklau, K.A. and N. Nergis, Controlling Dairy Nitrogen Emissions: A Dynamic Analysis of Herd Adjustment, Ground Water Discharges, and Air Emissions, Annual Meetings of the American Agricultural Economic Association, Long Beach, CA, July 2006.

Collaborative Efforts

This project has benefited greatly from discussions with Dr. Thomas Harter, Cooperative Extension Specialist, UC Davis.

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The Politics and Practice of Watershed Restoration

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University of California, Berkeley

In the last two decades, watershed restoration has dramatically increased in both popularity and practice, yet the social and environmental outcomes of restoration remain ambiguous. This research addresses three central questions: 1) What is watershed restoration accomplishing on-the-ground?, 2) Who and what primarily benefit from dominant restoration practices?, and 3) How is watershed restoration influenced by social factors, including the political economy of water use along with legal and institutional frameworks of water management.

In the last two decades, watershed restoration has dramatically increased in both popularity and practice. California has led the way with multi-billion dollar bonds being approved by voters for environmental improvements and a plethora of public and private funding sources providing grants for restoration activities. Yet, the social and environmental outcomes of restoration remain ambiguous and critics charge that restoration has not fulfilled its promise. This research addresses three central questions: 1) What is watershed restoration accomplishing on-the-ground?, 2) Who and what primarily benefit from dominant restoration practices?, and 3) How is watershed restoration influenced by social factors, including the political economy of water use along with legal and institutional frameworks for water management?

Our main research objective is to enhance watershed management in California by improving our understanding of the coupled social – environmental systems. To do this, we integrate institutional analyses, archival research, document and literature reviews, interviews, post-project appraisals, and spatial data analysis in order to make explicit the broader webs of social relations that shape restoration and explore the consequences for different groups of people and organisms. Thus far, we have collected data on nearly 800 restoration projects in the Russian River watershed, creating a Geographic Information Systems (GIS) database of this data along with land use and demographic information. We are in the process of analyzing dominant practices and trends over time. Preliminary results suggest that restoration projects most often occur at a site-specific scale and the majority are characterized as riparian, in-stream, or road-related improvements. One of the co-PIs, G. Mathias Kondolf, co-authored an important article on restoration accomplishments nation-wide utilizing this data, which was recently published in the journal *Science*.

In addition, nearly 50 interviews have been completed with individuals involved in restoration in the Russian River watershed. These interviews have revealed the dynamic nature of restoration as a concept, signifying everything from the revival of a cultural connection to the land, to the restoration of particular ecosystem processes, to the creation of a new industry. Interestingly, one of the major issues absent from discussions of watershed restoration is the role of water management. California Senate Natural Resources and Water Committee Principal, Bill Craven, remarked that restoration has been limited in its impact by not addressing important issues like water use (California Watershed Day). Current research is examining why this disconnect has developed by analyzing the political economy and institutional framework of water management in the Russian River area and how it creates both opportunities and constraints for watershed restoration.

Publications

Bernhardt, E.S., M.A. Palmer, J.D. Allan, G. Alexander, K. Barnes, S. Brooks, J. Carr, S. Clayton, C. Dahm, J. Follsted-Shah, D. Galat, S. Gloss, P. Goodwin, D. Hart, B. Hassett, R. Jenkinson, S. Katz, G.M. Kondolf, P.S. Lake, R. Lave, J.L. Meyer, T.K. O'Donnell, L. Pagano, B. Powell, and E. Sudduth, Synthesizing U.S. river restoration efforts, *Science*, 2005, 308:636-637.

Kondolf, G.M. River restoration and meanders, *Ecology and Society*, in press.

Langridge, Ruth, Christian-Smith, Juliet, and Kathleen Lohse, Access and Resilience: Analyzing the Construction of Social Resilience to the Threat of Water Scarcity, *Ecology and Society*, in press.

Christian-Smith, Juliet, Beneath the Surface: The Politics and Practice of Watershed Restoration, Insights from the Russian River Watershed, Northern California, Ph.D. dissertation, expected filing date 12/2006.

Professional Presentations

Christian-Smith, Juliet, A political ecology of watershed restoration: insights from Northern California, International Symposium on Society and Resource Management, Vancouver, Canada, June 2006.

Collaborative Efforts

National Science Foundation, Biocomplexity Working Group, UC Berkeley: Adina Merenlender, Jeff Romm, Matt Kondolf, Vince Resh, Ruth Langridge, Kathleen Lohse, David Newburn, Leah Beche, Matt Deitch, and Jeff Opperman. The WRC grant has allowed aspects of this collaboration to continue and to culminate in several publications focused on water policy and management issues in Northern California.

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Salinity/Drainage Program

This program encompasses research and/or extension activities that address and contribute to the resolution of the salinity-drainage-toxics problem in the western San Joaquin Valley. Topics include the fate and impacts of various selenium species in the environment; relationships between wetland management and the discharge of salt and/or toxic chemicals to the San Joaquin River; long-term management of retired lands; relative impacts of boron on the long-term consequences of using drainage water for irrigation; and technology development for real-time monitoring of water for chemical constituents of concern.

Membrane Desalination of Agricultural Drainage Water

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This project focuses on evaluating the integration of accelerated precipitation softening (APS) for scale mitigation with membrane RO desalting to enable high RO recovery. The technical and economic feasibility of the integrated APS/RO process and the practical recovery limits are being evaluated via laboratory evaluation using both brackish water field samples and model solutions along with computational model simulations.

The salinity of brackish groundwater in the San Joaquin (SJ) Valley ranges from about 2000 to as high as nearly 29,000 mg/L total dissolved solids (TDS); in recent years, membrane desalination has been proposed as the practical technology to reduce this. Membrane desalination for SJ Valley brackish water would have to be carried out at relatively high water recovery in order to reduce the volume of generated reverse osmosis (RO) concentrate. However, at high water recoveries the concentration of mineral salt ions, on the feed-side of the membrane, may increase to levels that exceed the solubility limits of sparingly water soluble mineral salts (e.g., calcium sulfate, calcium carbonate and barium sulfate). As a result, these mineral salts may crystallize on the membrane surface and also precipitate in the bulk feed solution and deposit onto the membrane surface. This results in mineral scale build-up on the membrane surface that leads to permeate flux decline, shortening of membrane life, and consequently, reduction in process efficiency, increased operational cost and limitation on the maximum achievable product water recovery.

High recovery can be achieved if mineral salt scaling is alleviated. Accordingly, the present project focuses on evaluating the integration of accelerated precipitation softening (APS) for scale mitigation with membrane RO desalting. APS treatment serves to de-supersaturate the RO primary feed or concentrate stream with respect to mineral salt scalants of concern. The demineralized stream can then be further desalted in a secondary RO stage to reach the target product water recovery. In the first phase of the project, a systematic theoretical thermodynamic solubility analysis was carried out to evaluate the limits on product water recovery due to mineral salt precipitation. This was done for five source water locations in the SJ Valley. The analysis revealed that, even with the use of antiscalants and acidic pH adjustment, primary RO recovery in the five different locations would be in the range of 54%-76%. Recovery in excess of 90% is feasible, via secondary RO desalting of the primary RO concentrate, provided that the appropriate amount of dissolved calcium is removed by APS in order to de-supersaturate the RO concentrate. A design methodology was developed to determine the feasible primary RO recovery limit, the required percent of calcium removal by APS and the operating pH for the secondary RO stage. Such an approach will enable streamlining future RO pilot studies and aid in process scale-up.

Preliminary successful experiments were carried out to demonstrate the technical feasibility of the integrated RO-APS-RO desalting process. Diagnostic methods were developed to assess APS kinetics and the associated efficiency of reducing mineral scaling propensity. Moreover, based on analysis of field water samples, the limits on primary RO recovery, as well as the pretreatment needs for successful RO desalination have been identified. Continuing studies will provide additional valuable data necessary to estimate the cost of achieving up to 95% desalination recovery. Based on initial cost analysis, it is estimated that water desalination cost for the integrated RO-APS-RO process is in the range of typical brackish water desalination. However, it is noted that the reduction in concentrate volume could reduce the overall water production cost and make the process more environmentally acceptable relative to lower recovery brackish RO desalting processes.

Publications

Rahardianto, A., J. Gao, C. J. Gabelich, M. D. Williams and Y. Cohen, "Accelerated Precipitation Softening for High Recovery Desalination of Low Salinity Brackish Water," *J. Membrane Science*, accepted.

Rahardianto, A., W-Y Shih, Lee R-W. and Y. Cohen, "Diagnostic characterization of gypsum scale formation and control in RO membrane desalination of brackish water", *J. Membrane Science*, 222, 1-14 (2006).

Shih, W-Y, A. Rahardianto, R-W. Lee and Y. Cohen "Morphometric Characterization of Calcium Sulfate Dihydrate (Gypsum) Scale on Reverse Osmosis Membranes," *J. Membrane Science*, 252, 253-263 (2005).

Professional Presentations

Cohen, Y. "High Recovery RO Desalination of Brackish Water," Invited Presentation, 4th Chemical Engineering Conference for Collaborative Research in Mediterranean Countries, Le Meridien Hotel, Dead Sea, Israel, Jan. 9-11, 2006.

Cohen, Y., "Membrane Surface Nano-Structuring: Selectivity Enhancement, Fouling Reduction and Mineral Scale Formation," Invited Presentation, U.S. - Israeli Workshop on Nanotechnology for Water Purification, Arlington, VA, Mar. 13-15, 2006.

Cohen, Y., "Membrane Desalination of Agricultural Drainage Water - Opportunities and Limitations," Invited Presentation, Salinity Drainage Conference, Water Resources Center, Sacramento, CA, Mar. 29, 2006.

Cohen, Y., "Desalination Process Limitations and Enhancements," Invited Plenary Presentation, California/Nevada Section American Water Works Association (CA/NV AWWA) 2006 Spring Conference, Burlingame, CA Apr. 24-28, 2006.

Rahardianto, A., B.C. McCool, S. Rezvani and Y. Cohen, "High Recovery Desalination of Agricultural Drainage Water: Integration of Accelerated Seeded Precipitation with RO Membrane Desalination," CA/NV AWWA 2006 Spring Conference, Burlingame, CA Apr. 24-28, 2006.

Cohen, Y., "Desalination Process Development and Diagnostic," First Western Workshop on Water Technology Research," UCLA, Los Angeles, CA, Sep. 29, 2006.

Collaborative Efforts

The California Department of Water Resources, Salinity Drainage Program has provided water samples from various locations in the SJ Valley. Water quality analysis was also provided for all samples. All of the above was provided as in-kind support.

The Metropolitan Water District of Southern California has provided antiscalant samples that were utilized in this study. A membrane concentrator, provided by MWD as in-kind contribution, was utilized in this study to evaluate high recovery RO desalination.

OLI Systems (Morris Plains, NJ) provided, at a significant discount, the LabAnalyzer 2.0 thermodynamic simulator that was utilized in this study for solubility analysis.

Hydranautics and Koch Membrane Systems have provided membranes as in-kind contribution for use in the present study.

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Bioaccumulation and Biotransformations of Organic Material-Borne Selenium in Mosquitofish

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Organic selenium (Se) species in drainage water and organic material extract cannot be speciated by HPLC-HGAAS.

Seleniferous organic materials deposited in the sediment and suspended in the water column may be a dietary food source subject to bioaccumulation by wetland organisms. We proposed to develop a method to determine organic selenium (Se) species in wetland organic materials, and then to use this method to investigate the bioaccumulation and biotransformations of organic material-borne Se in mosquitofish.

We conducted a series of tests to speciate organic Se species (selenomethionine, selenocystine, Se-methylselenocysteine, dimethylselenoxide, and dimethylselenonio-propionate) using high performance liquid chromatography (HPLC) connected with hydride generation atomic absorption spectrometry (HGAAS). Results have shown that several organic Se species can only be separated in deionized water. When drainage water and organic material extracts containing spiked organic Se species were used, organic Se species could not be separated by HPLC-HGAAS; indicating that salts in the drainage water and organic compounds in the organic material extract affect separation and determination of organic Se species by HPLC-HGAAS.

Publications

Zhang, Yiqiang, and William Frankenberger, Jr., Removal of selenate in river and drainage waters by *Citerobacter braakii* enhanced with zero-valent iron, *Journal of Agricultural and Food Chemistry*, 2006, 54:152-156.

Zhang, Yiqiang, and William Frankenberger, Jr., Removal of selenium from river water by *Enterobacter taylorae* in an organic carbon coated sand column, *The Sciences of Total Environment*, 2005, 346: 280-285.

Zhang, Yiqiang, Juanfang Wang, Chris Amrhein, and William Frankenberger, Jr., Removal of selenate from water by zero-valent iron, *Journal of Environmental Quality,* 2005, 34: 487-495.

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Continued Investigation into the Interactions of Saline Drainage Water on Crop Tolerance to Boron

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Research with broccoli showed significant salinity-boron, salinity-pH, boron-pH and salinity-boron-pH interactions with respect to fresh weight, total biomass, head yield and water use efficiency. Salinity and boron can reduce emergence but effects are crop and variety specific.

An earlier salinity-boron interaction study with broccoli showed that salinity, regardless of the ionic composition, reduced boron's detrimental effect. Both stresses were damaging but their adverse effects were not additive. However, pH, a factor known to influence boron uptake, was not a variable. Therefore another greenhouse experiment was conducted in 2005-06, using broccoli grown in an elaborate sand tank system at the USDA-ARS, George E. Brown, Jr. Salinity Laboratory, to determine the interactive effects of salinity, boron and pH on broccoli (Brassica oleracea L., botrytis group**,** cv Seminis PX511018) performance including growth, yield, injury, and ion relations.

The irrigation treatments were prepared by adding various salts to modified half-strength nutrient solution to develop synthetic drainage water with a chemical composition characteristic of that found in the San Joaquin Valley. Five salinity levels (2.0, 5.0, 8.0, 11.0 and 14.0 dS/m) were tested at 2 boron concentrations (1.0 and 21 mg/L) under slightly acidic conditions (pH 6) and slightly basic conditions (pH 8). The experimental design was a 5x2x2 factorial with three replications.

ANOVA showed significant interactions of salinity-boron, salinity-pH, boron-pH and salinity-boron-pH with respect to fresh weight, total biomass, yield and water use efficiency. These interactions will be detailed in a model analysis but the overall finding from all of the interactions are that the individual effects of salinity, boron concentration, and pH are not simply additive. With regard to fresh fruit yield, increased salinity reduced yield but high boron added to treatments when the pH was maintained near pH 6 was not detrimental. However at pH 8, 21 mg/L B was extremely detrimental at low and high salinities. Interestingly, at moderate salinity levels (EC 5 – 11 dS/m) high boron did not further decrease yield. Therefore moderate levels of salinity (concentrations likely exposed to broccoli grown in rotation in reuse systems) protect that plant from boron toxicity under slightly basic conditions. Data on ion relations are still being processed.

A subsequent study was conducted in the sand tanks to determine the effects of salinity (2, 5, 8, 11 and 14 dS/m) and boron (1, 11, 21 and 31 mg/L) on cotton emergence. This is important since most experiments impose salinity and boron treatments after the plants are established and cotton stands in the field have been adversely affected by drainage water applied the previous season. Six cotton varieties, including both Pima and Acala types, responded differently. For some varieties, salinity and boron decreased the percent emergence after two weeks while for others, either salinity or boron (not both) reduced emergence. Interestingly, for one Acala variety (6100), boron additions up to 31 mg/L significantly increased emergence at the two higher salinity levels. For this variety, unlike the others, there was a significant salinity-B interaction.

The emergence of six vegetable crops under similar treatments were also evaluated. Increased boron from 1 to 31 mg/L only decreased the emergence of cantaloupe seedlings. The other 5 vegetables tested were unaffected. Neither broccoli nor lettuce was impacted by increased salinity to the highest level (12.5 dS/m). The emergence of cantaloupe, tomato, corn and cucumber seedling, on the other hand, were reduced 45 to 65% at the highest salinity level. This effect was much greater than those cotton varieties affected by salinity.

Professional Presentations

Grattan, Steve, Catherine Grieve, Jim Poss, Don Suarez, Tim Smith and Andre Lauchli. Can broccoli tolerate higher concentrations of boron under saline conditions? World Congress of Soil Science. Philadelphia, PA July 10-14, 2006

Collaborative Efforts

This research project is a collaborative effort between the University of California at Davis and the USDA-ARS George E. Brown, Jr. Salinity Laboratory.

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Implementation of Wetland Adaptive Water Quality Management Strategies under Real-Time Salinity TMDLs

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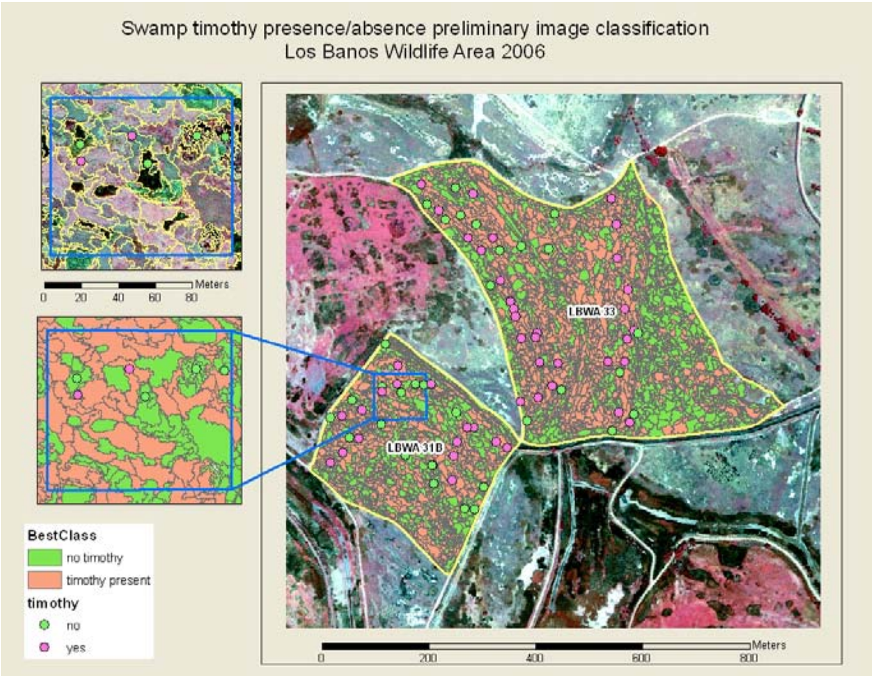
A comprehensive ecological monitoring program is described in this proposal to measure and quantify potential long-term impacts of real-time wetland salinity management on wetland habitat and the health of the biological resource.

This project is aimed at developing and testing a pilot-scale real-time water quality management relevant to managed wetlands in the San Joaquin River Basin. Restoration and improvement of seasonal wetlands is an important part of the overall plan to improve water and salinity management in the Central Valley and the San Francisco Bay-Sacramento Delta region. The use of seasonal wetland habitat by over-wintering waterfowl and shorebirds degrades the water supply delivered to private duck clubs and to State and Federal Refuges from the Delta. Returning drainage from the wetlands contains further elevated salts, carbon and nutrients as a result of bird use, the life cycle of other biota and invertebrates, decaying aquatic vegetation, wind-blown sediment and natural evapotranspiration processes.

This research centers around six pairs of experimental seasonal wetland units in the Grassland Water District. For each pair we are comparing traditional management practices with a delayed seasonal draw-down timed such that it provides benefits to San Joaquin River water quality. Progress over the first year of the project has been made in five main areas:

- Radio-telemetry stations equipped with autosamplers, electrical conductivity, temperature and stage sensors have been constructed and are undergoing testing at the inlet and outlet of each wetland unit to measure salt fluxes under both management regimes.
- High resolution multispectral imagery was acquired for the project study area. Features of this imagery are now being classified and checked for accuracy using ground truth data. A map showing estimated presence or absence of *Crysis schoenoides* (swamp timothy) at Los Banos wildlife area is shown below.
- Fabrication of an ATV-mounted electro-magnetic soil salinity sensing system used to map seasonal wetland soil salinity in traditional and adaptively managed units.
- Design and fabrication of stationary sensor arrays observation of wetland pond salinity. The stationary arrays, or javelins, will enable continuous monitoring of moist soil conditions in the wetlands.
- Design and fabrication of a robotic device called “Sensoduck” will enable pond salinity and temperature mapping through remote controlled and eventually autonomous adaptive sampling routines.

Supplemental funding, through a California Department of Water Resources Proposition



204 grant, will support instrumenting the wetland units for observing spatiotemporal salinity and temperature distributions in pond water and underlying sediments. This will enable us to gain a process level understanding of the distributed moist soil plant conditions which prevail under the two management practices.

Professional Presentations

Quinn, Nigel W.T. and Josephine R. Burns, New Tools for Ecological Impact Assessment in Managed Seasonal Wetlands, LBL ES Departmental Review, April 11-12, 2006. (poster)

Harmon, Thomas C., Roger Bales, Samuel Traina, Deborah Estrin, and William Kaiser, Observing, Forecasting, and Managing a CLEANER California Water Cycle, American Geophysical Union Annual Spring Meeting, Baltimore, MD, May 24, 2006.

Harmon, Thomas C., John Ewart, Christopher Butler, and others, CENS Contaminant Transport Observation and Management Research Overview, Center for Embedded Networked Sensing (CENS) Annual Site Visit, Los Angeles, CA, June 14, 2006. (poster)

Burns, Josephine R. and Nigel W.T. Quinn, LBNL-60747: Use of Geospatial Technologies to Compare Environmental Impacts of Wetland Delayed Drawdown in California's San Joaquin Basin, Society for Conservation GIS, June 24-28, 2006. (poster)

Burns, Josephine R., Fuzzy Classification of Wetlands Vegetation Using Object Based Image Segmentation, USBR project review at LBNL, January 17, 2006.

Burns, Josephine R., Classification of Wetlands Vegetation Using Object Based Image Segmentation, CAMFER seminar, UC Berkeley, February 15, 2006.

Collaborative Efforts

Josephine Burns and Katherine Burns, *Lawrence Berkeley National Laboratory;* John Beam, William Cook, and Ricardo Ortega, *California Department of Fish and Game;* Don Marciochi, *Grassland Water District;* Joe Tapia, Ernie Taylor, and Stuart Itoga, *California Department of Water Resources;* Deborah Estrin, *UCLA* and Guarav Sukhatme, *USC.*

California DWR participation is through a Proposition 204 grant to support supplemental work on this project.

UCLA and USC participation is through the National Science Foundation Center for Embedded Networked Sensing (CENS).

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Salt Dynamics in Non-Riparian, Freshwater Wetlands

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We are investigating the salinity dynamics of seasonal wetlands in the San Joaquin River basin, with an emphasis on salinity exchange with wetland soils and how different flooding strategies influence the long-term salinity of the wetlands. A combination of field, laboratory and numerical analysis is being applied to understand the detailed interaction between the soil and water columns and the potential for salinity to be retained in wetland soils.

We are investigating the salinity dynamics of seasonal wetlands in the San Joaquin River basin, with an emphasis on salinity exchange with wetland soils and how different flooding strategies influence the long-term salinity of the wetlands. In the first year of this grant, we have completed the field data collection and laboratory experiments, and have begun some numerical analysis of the relevant processes.

The field data collection consisted of time series of conductivity (EC), temperature and depth at multiple locations in the wetland under study, plus velocity measurements at two locations in a channel that bisects the wetland. These time-series spanned the entire flooded period, and were supplemented by several spatial surveys of EC and temperature collected by towing a conductivity-temperature probe on a floating raft around the wetland. These data have been processed and are now ready for a more complete analysis in the coming year.

The laboratory experiments we have performed focused on how flood-up and draw-down strategies, as well as vegetation types, affect the retention of salts in the soil column. We used four different flood-up and draw-down protocols to span the management strategies typically pursued (Table 1). In each case, the flooding and draining of the soil column was performed on multiple soil columns characterized by a range of vegetation types representative of the actual field site. Between the flood-up and draw-down stages, the water column was replaced with high EC waters to simulate the effects of evaporation in the field. Data recorded in each experiment included detailed time-series of EC and temperature at three elevations in the soil-water column. Just as in the case of the field observations, these measurements are now complete, and the data has been processed and prepared for analysis in the coming year.

Exp	Flood-Up	Draw-Down
1	Fast (2-3 days)	Fast (2-3 days)
2	Fast (2-3 days)	Slow (10-12 days)
3	Slow (10-12 days)	Fast (2-3 days)
4	Slow (10-12 days)	Slow (10-12 days)

Table 1: Laboratory Experiment Summary.

Numerical work currently underway is focused on a vertical model of the soil-water columns being explored in the laboratory. We have developed a one-dimensional advection-diffusion equation that allows a spatially-variable diffusion to be specified. This model is being used to compute time trajectories for salinity in the soil-water columns, which will be compared with the observed time series. In addition to traditional time-series comparisons, we will focus our analysis on defining patterns in the time variability, particularly hysteresis (if it exists) and phasing of constituents relative to flood-up and draw-down. While these comparisons may seem qualitative in nature, they actually represent a clearer test of our understanding of the underlying processes than a detailed comparison of time variability would. The goal in this analysis is to determine whether the flooding-drying strategy leads to changes in the underlying processes that govern salinity retention in soils and the return of those salts to the water column during flood-up.

Collaborative Efforts

The PI's research group includes two PhD students pursuing research related to the restoration of wetlands on the perimeter of San Francisco Bay. Many of the properties to be restored are currently salt ponds (as in the case of the South Bay Salt Pond Restoration Project, SBSPRP). An open question for many of these activities is what role the exchange of constituents between the soil column and the water column will play in determining the state of the restoration project. In most of these cases, the flooding and drying of the area will be on the tidal timescale, which is considerably faster than the flooding and drying being analyzed in this work, but the concepts may prove to be transferable.

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Mechanisms of Arsenic Accumulation and Biogeochemistry in Evaporation Basins

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Arsenic exists mainly as arsenate (oxidized form) in subsurface agricultural drainage waters but when evapoconcentrated in evaporation basins some of the arsenate is transformed into reduced forms such as arsenite and organic arsenic, especially in the reduced terminal cells of the evaporation basin. Although sinks of arsenic were identified, arsenic behaved somewhat similar to salinity, increasing with increasing evapoconcentration along the water flow pathways from Cells 1 to 10.

Disposal of saline subsurface drainage waters from croplands into evaporation basins (ponds) occurs in the San Joaquin Valley in areas with no opportunities for disposal into the San Joaquin River. In addition to excess salts, these agricultural drainage waters contain elevated concentrations of trace elements including arsenic, a potentially high risk element with little information about its fate.

The objective of this study was to evaluate the biogeochemical conditions under which arsenic accumulates in a specific agricultural subsurface drainage disposal site. The goal was to better understand arsenic transformations and speciation, including their fate in evaporation basins.

The study site is South Evaporation Basin in the Tulare Lake Drainage District, a 726-ha facility containing 10 cells with water flowing by gravity and in series between the cells. We examined monthly water chemistry and arsenic concentration and speciation along the water flow path between cells. Additionally, we conducted comprehensive sampling within Cell 1 which was the first cell to receive the drainage water, and Cell 9, towards the terminal end of the flow path in which the water had been subjected to substantial evapoconcentration. Cross-sectional water samples from the top and bottom layers of the water column and surface sediments within Cells 1 and 9 were comprehensively analyzed.

Evapoconcentration was evident in this drainage disposal facility, resulting in increasing salinity along the flow path from an EC of 12 dS/m to about 240 dS/m. Arsenic concentrations also increased with increasing EC along the water flow path, exhibiting a somewhat conservative behavior.

The redox condition in Cell 1 was oxidized and in Cell 9 reducing, as indicated by lower concentrations of dissolved oxygen and nitrate, and higher concentrations of ferrous and sulfide ions. Increases in reduced arsenic species, such as arsenite (As(III)), monomethylarsonic acid (MMAA) and dimethylarsinic acid (DMAA), were found towards the terminal end of the flow pathway. However, arsenate (As(V)), the dominant form of arsenic in the subsurface drainage water, remained at 50% or greater in all pond waters sampled.

Sequential extractions of the sediments indicated that carbonates played an important role in immobilizing arsenic into the sediments. However, reducing conditions can mobilize sorbed arsenic on oxy-hydroxide mineral phases.

These sink mechanisms did not significantly reduce arsenic concentrations within the cells. Arsenic behaved nearly the same as salinity from the continuous inputs of arsenic-containing fresh drainage water into the system and the resulting evapo-concentration up to 20-fold in the terminal end of the flow pathway.

Preparing for spatial sampling of the water column and sediments within a cell of the evaporation basin.

Publications

Gao, S., J. Ryu, K.K. Tanji, and M.J. Herbel. Arsenic Accumulation and Speciation in Evaporating Waters of Agricultural Evaporation Basins. Chemosphere 2007, 67:862-871.

Professional Presentations

Gao, S., K.K. Tanji, and J. Ryu. Chemical Behavior of Selenium and Arsenic in a Saline Agricultural Drainage Disposal Pond Facility. International Salinity Forum, Riverside, CA, April 25-27, 2005.

Gao, S., J. Ryu, and K.K. Tanji. Arsenic Accumulation in Evaporation Basins for Agricultural Drainage Disposal, California, USA, 18th World Congress of Soil Science, Philadelphia, PA, July 9-15, 2006.

Collaborative Efforts

This study was conducted in Tulare Lake Drainage District's (TLDD) South Evaporation Basin. TLDD assisted us in monitoring water flows and reading staff gauges in the cells. We also received assistance from Novalek, Inc., for spatial sampling of the water column and sediments within Cells 1 and 9. Dr. M.J. Herbel of the US Salinity Laboratory helped us interpret some of the arsenic data.

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Sustainable Ecosystems under Land Retirement

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There is a potential to use the retired land as wildlife habitat to improve the ecological system in the western San Joaquin valley without any serious negative consequences.

The absence of adequate drainage due to topographic and environmental constraints has forced the western San Joaquin Valley to tackle problems of shallow water tables with high salinity in general, and specific toxic trace elements in particular. It is estimated that by 2040 approximately 160,000 to 225,000 ha (400,000 to 554,000 ac) would become unsuitable for irrigated agriculture if no actions were taken to remedy drainage problems.

Land retirement was proposed as one strategy to reduce drainage-related problems. In this approach, lands that were characterized by low productivity, poor drainage, shallow water tables, and high groundwater selenium concentrations would be removed from agriculture.

The retired agricultural lands could potentially be used as a wildlife habitat to improve the ecological systems in the valley. Other potential land uses such as grazing and dry land farming are also envisaged.

However, there is also a possibility of land retirement causing negative effects such as excessive accumulation of trace elements and salts on the land surface and the establishment of undesirable weed communities. Excessive salt accumulation might result in little or no plant growth and vegetation cover causing wind blown salt problems downwind. The results of hydrologic and soil modeling studies have indicated that without implementation of special management techniques, there is serious danger of retired lands becoming excessively salinized and seleniferous.

A part of the Kerman ecological reserve. The nature of the natural landscape prior to massive irrigation activities changed it. 6/21/2006

With a view to study various land retirement scenarios leading to a formulation of sustainable ecosystem management strategy, the objectives of the study are to,

a) Develop, calibrate and validate a numerical model based on a proven modeling system that can be used to simulate major processes occurring in the land phase of the hydrological cycle. The model should be able to simulate unsaturated-saturated water flow and solute transport, subject to root water uptake.

b) Evaluate and recommend land retirement management strategies that will promote/maintain a sustainable agriculture production system in the region.

c) Evaluate and recommend land retirement management strategies that will promote a sustainable ecosystem.

The goal is to achieve these objectives through the use of the calibrated hydro-salinity model that integrates subsurface hydrology with reactive transport to obtain initial salinity and shallow groundwater conditions. The results so far obtained have been compared with actual field measurement records.

The UNSATCHEM model is being used to evaluate the sustainability of various land uses as a function of root water intake functions, initial salinity concentration and shallow groundwater level. The use of different native plants is being investigated. Field data related to salinity and shallow groundwater level from the Bureau of Reclamation's Land Retirement Demonstration Project is being used guide the modeling effort. The results of the modeling effort will be used to recommend possible management choices as to the use of retired land. Finally the integrated regional hydro-salinity model will be used to evaluate the sustainability of the proposed ecosystem.

The preliminary results from the study indicate that under fallow land conditions, the shallow water level declines without the sustained buildup of salts in the soil profile.

Alkali sink ecological reserve along HW 180. It has a relatively lush landscape with Allenrolfea, a native perennial shrub. 6/21/2006

Collaborative Efforts

Collaborative contribution from Stephen L. Lee, and Beatrice A Olsen of the Land Retirement Demonstration Project resulted in a site visit to the project's demonstration site in western Fresno County. Groundwater quality data and the groundwater level data from the Tranquility site for the period 1999-2004 were also provided by Stephen L. Lee.

Gerald D. Robbins Jr., Bureau of Reclamation, Project Manager, Mid-Pacific Region has provided the maps in jpg format showing the proposed land retirement area.

Native species nursery used by USBR to test the efficacy of putting different kinds of plants in the land retirement plots. 6/21/2006

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Irrigation Management Program (Prosser Trust)

This program encompasses research and/or extension activities that address a broad spectrum of topics related to irrigation management. Topics include crop-specific studies for regulated time-related deficit irrigation that reduces transpiration with minimal impact on yield of the marketable product; identification of crop-specific management practices for reducing the evaporation component of evapotranspiration without inducing an increase in transpiration; and evaluation of irrigation management from a water quality benefit perspective as well as a production perspective.

Regulated Deficit Irrigation of Alfalfa

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Deficit irrigation of alfalfa in July and August is being investigated as a source of water for nonagricultural uses during water short years by reducing the seasonal crop evapotranspiration. Results of 2005 showed deficit irrigation reduced the seasonal crop evapotranspiration by 289 mm, but also reduced yield of the last two harvests by 41 to 65% of fully irrigated alfalfa.

Alfalfa is California's single largest agricultural water user due to its large acreage and long growing season, using 494,000 to 679,000 ha-m (4 to 5.5 million-acre feet) of water each year. The California Department of Water Resources is interested in deficit irrigation of alfalfa as a strategy for providing water for transfer elsewhere. Irrigation would be terminated during July and August when yields are relatively small and the "saved" water used elsewhere. The amount of transferable water is the difference in the evapo-transpiration (ET) between fully-irrigated and a deficit-irrigated conditions; however, no information exists on this difference.

Evapotranspiration was determined in a commercial field using the eddy covariance and surface renewal energy balance methods in a fully irrigated part of the field, and the surface renewal method in the deficit irrigated part of the field. In addition, alfalfa yield, applied water, canopy coverage and plant height measurements were made in both parts of the field.

The fully-irrigated alfalfa was irrigated according to the irrigator's normal practices. The 2005 deficit-irrigated treatments consisted of no irrigation during August with no fall irrigation, and no irrigation during August followed by a September irrigation. A new site was selected for the 2006 project. The 2006 deficit-irrigated treatment (ongoing until December 2006) consists of no irrigation during July and August with no fall irrigation. Each treatment consisted of three alfalfa checks with border checks between the irrigated and deficit irrigated treatments. The border checks were necessary to prevent water flow through cracks in the soil from the irrigated treatments into the deficit irrigated treatments. The field scale approach was used to obtain the field-wide conditions experienced by commercial agriculture. A randomized replicated experimental design was not feasible because of the constraints caused by the use of a commercial field.

Deficit irrigation greatly reduced alfalfa yield in 2005 (Table 1). Yield reductions due to deficit irrigation generally ranged from 41 to 65% of the fully-irrigated treatments. However, yield of the 7th harvest recovered due to the September irrigation. Yield data of 2006 are currently being analyzed.

Cumulative ET_c in 2005 (no fall irrigation) was 1,222 mm (48.1 inches) for the fully-irrigated treatment. Deficit irrigation (no irrigation) started on July 25. Cumulative ET_c between July 25 and December 6 (end of measurement period) was 528 mm (20.8 inches) for the fully irrigated treatment and

289 mm (11.4 inches) for the deficit irrigated treatment for a difference of 239 mm (9.4 inches). Differences in ET_c for July 2006 were 65 mm (2.6 inches).

Table 1. Treatment yields of 2005. The 6th and 7th harvests occurred on August 23 and October 6, respectively. The numbers in the parenthesis are the yield reduction in percent of the full yield.

	Yield (Mg/ha)			
	6th Harvest	7th Harvest	Total	Yield Reduction
Full	1.46	0.98	2.42	
Deficit (no Sep. irrig.)	0.51 (65)	0.58 (41)	1.37	1.05
Deficit (Sep. irrig.)	0.72 (51)	1.16	1.90	0.51

Professional Presentations

Putnam, Dan, Steve Orloff, Blaine Hanson, Harry Carlson. Field Studies on Deficit Irrigation of Alfalfa. 2006 California Plant and Soil Conference, Visalis, CA, Febrary 2006.

Hanson, Blaine, Dan Putnam, Rick Snyder. Deficit Irrigation of Alfalfa as a Strategy for "Saving" Water for Nonagricultural Uses, Soil and Water Conservation Society, Keystone, CO, July 2006.

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Irrigation Management Improvements for San Joaquin Valley Pima Cotton Systems

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Pima cotton, Gossypium barbedense*, has different water use patterns than Upland cotton plantings,* Gossypium hirsutum*, previously used for irrigation studies. This research narrowly defines water scheduling practices and points out opportunities for improving water use efficiency leading to higher productivity per unit of water applied for Pima cotton.*

While Pima cotton, *Gossypium barbedense*, was first grown in California in the 1920's, it wasn't until 1991 that large-scale acreage was approved for planting following changes in the one-variety law established by the San Joaquin Valley Quality Cotton Control Board. Since that time, market conditions favoring very high quality lint have led to Pima cotton acreage increases to 273,000 acres with Upland, *Gossypium hirsutum*, cotton plantings steadily declining to 256,000 acres in 2006. Combined irrigation water applications for these two crops are estimated at over 1.5 million acre feet statewide, and options to reduce applied irrigation water without adversely impacting crop productivity are needed.

When compared to the common upland varieties grown throughout the US cotton belt, Pima cotton's more indeterminate growth habit led growers and researchers to suspect that its water use characteristics were different from those of the more traditional plant types and began to document changes in crop water use. Our work in this study is aimed at developing additional crop water use information for Pima cotton, validate the water stress guidelines that have been proposed for the crop, increase irrigation management extension outreach activities, and document the value of deficit irrigation practices as a method for improving water use efficiency.

One key element that separates irrigation management of cotton from that of other crops is cotton's ability to sustain modest water deficits without sacrificing large yield or quality losses. While peak productivity comes from meeting the full water requirement of the crop, it is common that the amount of water applied greatly surpasses the amount of water required by the crop. These inefficiencies in applied water combined with improper timing of irrigation events, results in low water use efficiency.

Cotton efficiently takes up water from the root zone and transports it to the leaves for evapotranspiration (ET). Upon soil drying between irrigation events, cotton leaves and

A grower and project cooperator interested in conserving water on-farm, Jeff Yribarren is seen here with Pima cotton.

the root system begin to recognize water stress events and the consumption of water is reduced without creating sudden and dramatic changes in water stress as is the case for many other agricultural crops. This unique feature allows water stress to accumulate over a longer period without great impacts on crop quality or productivity. By monitoring crop water status in addition to soil water status, we are developing soil and plant based water management approaches that result in improved timing of irrigation events. Working to better control the frequency and duration of stress periods between irrigations, we can limit premature irrigation scheduling resulting in fewer irrigation events, and minimize yield loss when water becomes very expensive or is unavailable.

Field trials were conducted on west side Fresno County farms and at the West Side Research and Extension Center (WSREC) near Five Points, CA. During the 2005 production season, we conducted our studies on three farm sites; in 2006 we are evaluating one grower site and one WSREC site.

Our 2005 season irrigation studies used a wide range of applied irrigation volumes which enabled us to evaluate water deficit treatments that ranged from low water stress treatments that maximized yields to moderate stress treatments that significantly impacted crop productivity. The timing, duration and magnitude of water stress as measured by the pressure chamber was confirmed to be a very useful tool in scheduling irrigation events and determining when crop water stresses are significant enough to impact yield. While minor yield reductions may have occurred when imposing early and mid-season crop stress, we found that late season water scheduling played a major role in determining the magnitude of yield loss in pima cotton. This is contrary to many of the studies in Upland cotton that have shown that modifying late season irrigation cutoff dates typically plays a more subdued role in reducing yield and crop quality. The reasons for this difference might be explained by the characteristics of fruit production for this crop. Pima cotton requires a fruit set period of more than 45 days whereas Upland cotton types set fruit in 30 days. This, combined with the fact that a larger percentage of bolls are set late in the fruiting cycle, appears to change the crop's sensitivity to late season plant stress events.

This continuing work challenges the Pima cotton grower to manage irrigation water more carefully and to take advantage of opportunities earlier in the season to stretch irrigation events and conserve water. These findings will assist growers, irrigation districts and irrigation managers with the tools they need to increase water use efficiency in Pima cotton production systems. The experimental results and extension activities more narrowly define water scheduling practices and point out opportunities for improving water use efficiency leading to higher productivity per unit of water applied.

Collaborative Efforts

This project is part of a larger activity to improve irrigation management in cotton and elevate our understanding of crop water use in Pima cotton as compared with Upland cotton types. At the early stages of this activity we consulted with and gained support from the Westlands Water District and the United States Bureau of Reclamation. We acknowledge each agency for their financial and administrative support and would like to especially thank Gerald Robb with Westlands Water District and Tracy Slavin from the Bureau for their interest, ideas and support of water relations research in Pima cotton. We also acknowledge the efforts and invaluable support of UCCE Statewide Cotton Specialist Bob Hutmacher and UCCE Biometeorology Specialist Rick Snyder.

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Using Saline Groundwater for Large-Scale Irrigation of Pistachios Interplanted with Cotton

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Irrigation districts across the state have seen water costs increase 3 to 5 fold in the last ten years. Growers of low value field crops like cotton are struggling to remain profitable. Some marginally saline drain and groundwater associated with over 250,000 acres of the Westside of the San Joaquin Valley (SJV) can be used to increase water supply and decrease costs for irrigating salt tolerant crops. An earlier 9 year study with pistachios indicates that they are about as salt tolerant as cotton. This study is testing the economic and cultural viability of a large, commercial-scale interplanting of cotton and pistachios using saline irrigation water.

Cotton has long been known as a salt tolerant crop, but despite many small-scale field trials over 30 years almost no marginally saline water in the San Joaquin Valley of California is used for long-term production. Over the same period, water costs have increased four to tenfold while cotton prices have stagnated. In 1990, State Water Project allocations to Westside irrigation districts went to zero; unleashing California's infant water market with the establishment of "Emergency Pool" water that could be bought for $100/ac-ft. Given the salt tolerance of cotton and other rotation crops on the Westside (such as processing tomatoes), some studies investigated utilizing fresh water blended with drainage from tile systems as a means of boosting available water supplies for furrow irrigation. This approach generated some interest since yields were maintained at similar levels to fresh water irrigations, but required a high degree of management with the possibility of long-term residual salinity problems that growers did not want to deal with. Farmers are looking for less expensive, more secure water supplies and more profitable crops. Work in Iran, salt tank studies at the USDA Salinity Lab, Riverside, and a small plot, 9-year study in the southern San Joaquin Valley indicate pistachios may tolerate as much soil salinity as cotton (9 dS/m), but this has not been proven over the long-term on a commercial scale in California.

In 2004, twelve 19.5 acre test plots were set up in two adjacent 155 acre fields to test the use of saline water for commercial-scale cotton production and development of a new pistachio orchard using shallow subsurface drip tape. The fields have been farmed for more than 30 years, were well reclaimed (salinity averaged 1.57 dS/m to 3 feet) and had good drainage. We used fresh, blended and saline well water treatments (average EC of 0.5, 3.0 and 5.4 dS/m and boron @ 0.3, 6 and 11 ppm, respectively). The highest salinity treatment is more than 4 times as saline as almost all irrigation waters currently used in the SJV. The field was planted to solid pima cotton in 2004, with excellent yields near 4 bale/acre.

In 2005, pistachio rootstocks were planted in March on a 22 foot row spacing interplanted with four 38 inch rows of pima cotton. Pistachios were budded with a Kerman scion in July. All cotton yields were disappointing at around 2 bale/acre, but increase in pistachio trunk circumference was excellent. Plant tissue analysis showed a significant 0.5 to 3 fold increase in

	NO3-N (ppm)	NH4-N (ppm)	PO4-P (ppm)	K (%)	Na (ppm)	Cl (%)	B (ppm)	[1]Cotton Ht, ΔPistachio Circum (inch)	Cotton Lint Yield (lb/ac)	Total Salts Applied in Irrigation (lb/ac)
	Petioles 8/27/04				**Cotton 2004**			**9/14/04**	**10/6/04**	**Cotton'04**
Aque	170	75	368	1.84	570	2.58	34	42.2	1933	2,343
Blend	273	95	463	1.73	712	**3.23	37	*35.8	1928	11,390
Well	548	108	413	1.72	574	*3.00	37	38.8	2016	21,444
	Petioles 9/15/05				**Cotton 2005**			**9/15/05**	**10/19/05**	**Cotton'05**
Aque	403	53	760	2.06	605	2.71	42	41.6	954	2,305
Blend	158	40	573	1.79	539	*3.13	46	43.1	1129	10,144
Well	288	85	593	1.91	546	**3.38	**50	42.1	999	16,975
	Rootstock Leaves 9/15/05				**Pistachio 2005**			**10/19/05**		**Pistach'05**
Aque	63	160	580	1.02	222	0.27	194	1.06		1,742
Blend	55	128	545	1.06	220	0.27	**492	0.94		8,570
Well	65	148	500	1.08	314	**0.38	**673	0.94		14,782

*Significant @ 0.05 **Significant @ 0.01

[1]Cotton height @ irrigation cuttoff and increased pistachio trunk circumference from 6/2 - 10/19/05.

Table 1. Plant tissue nutrients, selected salts, growth characteristics, yield and applied salts.

chloride and boron levels in both cotton and pistachio (Table 1), but produced no toxicity symptoms. In spring 2006, cotton emergence was reduced by 14% (statistically insignificant) in the Well treatment compared to fresh water, and plant height was reduced earlier in the season. By the end of July, however, plant heights were about equal. Comparison of digital aerial analysis of the Normalized Difference Vegetation Index (NDVI) for August 2004 and 2006 also showed no treatment impacts. Thus, as of late summer 2006 there is no detriment to pistachio or cotton development due to salinity.

Every winter/early spring all treatments receive 8 to 12 inches of fresh water for leaching/preirrigation and cotton germination, followed by 21 to 26 inches of treatment water, depending on seasonal demand. Pistachios receive about 18 inches based on a 9.5 foot wide area (7.8 inches for the 22 foot row spacing). After three seasons of cotton irrigation this program results in about 6,900 lb/ac applied salt in the Aqueduct treatment and about 54,000 lb/ac in the Well treatment. Cotton will be grown one more season, and, with the continued help of the CA Pistachio Commission, the pistachios will be monitored at least until 10 years of age (2014).

Professional Presentations

Sanden, Blake, Louise Ferguson, Craig Kallsen and Dennis Corwin. 2006. Large-Scale Utilization of Saline Groundwater for Development and Irrigation of Pistachios Interplanted with Cotton. Vth International Symposium on Irrigation of Horticultural Crops, Mildura, Australia, August 2006.

Publications

Sanden, B.L., L. Ferguson, C. Kallsen, D. Corwin. 2006. Large-Scale Utilization of Saline Groundwater for Development and Irrigation of Pistachios Interplanted with Cotton. Proceedings of the Vth International Symposium on Irrigation of Horticultural Crops, *Acta Horticulturae* (accepted).

Collaborative Efforts

Aerial and ground GIS data are being analyzed in collaboration with Dennis Corwin of the USDA Salinity Lab, Riverside, CA and the majority of funding required for the next two years is provided by the CA Pistachio Commission in addition to funds from the UC Water Resources Center.

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