University of California Center for Water Resources

Annual Project Progress Report 2006 – 2007

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Dr. Laosheng Wu, Associate Director

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Table of Contents

RESEARCH PROJECT INDEX

Research Category I – Hydrology, Climatology and Hydraulics

Research Category II – Aquatic Ecosystems

Research Category II – Aquatic Ecosystems *(continued)*

Research Category III – Water Quality

Research Category III – Water Quality *(continued)*

Research Category IV – Water Development and Management Alternatives

Research Category V – Water Law, Institutions and Policy

Salinity/Drainage Program

Salinity/Drainage Program *(continued)*

Irrigation Management Program – Prosser Trust

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 hydrological databases for water resources management.

Monitoring California Water Resources from Space

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The goal of this work is to use current and emerging capabilities of satellite remote sensing 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 ground-water). 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 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 state-wide 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 the state's 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. In this past year, we have focused on objective 3, and initiated new work on objectives 2 and 5.

Progress on Objective 3. The Gravity Recovery and Climate Experiment (GRACE) satellite mission provides monthly estimates of column integrated land water storage by observing variations of Earth's gravity field. This estimate includes a contribution from all the components of land water storage, both above and below ground.

Despite being in the midst of a significant multi-year drought, GRACE-derived water storage in two of the largest river basins in the western United States (San Joaquin and Sacramento) show a positive trend during the period of 2003-2006 (Figure 1). In this study we took a closer look into the apparent discrepancy by analyzing the consistency between GRACE data over the combined Sacramento-San Joaquin basin region, and those obtained from basin-scale water balance computations.

While GRACE-derived estimates of change in storage over time bear close correspondence with those obtained from terrestrial water balance using individual estimates of precipitation (P) and evaporation (E) (Figure 2, blue line), large discrepancies are noted, particularly during 2004, when compared to

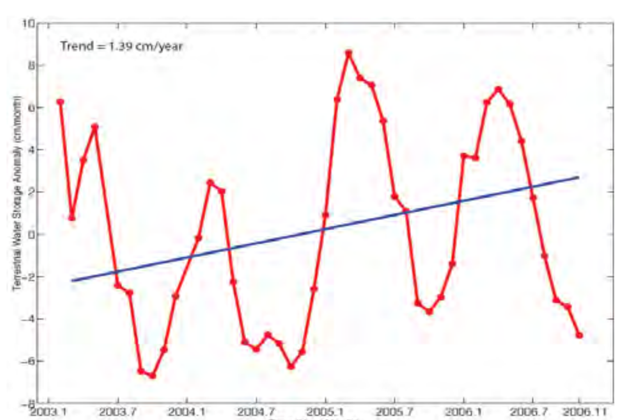

Figure 1. Water storage anomalies from GRACE for the Sacramento-San Joaquin drainage basin system.

those based on atmospheric moisture budget terms (Fig. 2, green line). For the purposes of this study, further analysis will utilize the terrestrial water balance computations. During the study time period, P has been increasing at a rate greater than that of evapotranspiration and streamflow.

When interpreting GRACE data, it is important to keep in mind that GRACE provides information on storage anomalies, relative to the average over the 2003-2006 time period. Although GRACE and the water balance data confirm that the increasing storage trend is real, the increase is relative to the average over that time period, and the average is low. Hence, the best explanation for the increasing storage documented by GRACE is that, as a result of a multi-year drought, storage levels became extremely low. In essence, increases in observed storage (GRACE) are only with respect to storage levels at the beginning of 2003 and can only contribute to reduce the storage deficit, based on severe drought conditions in place in early 2003.

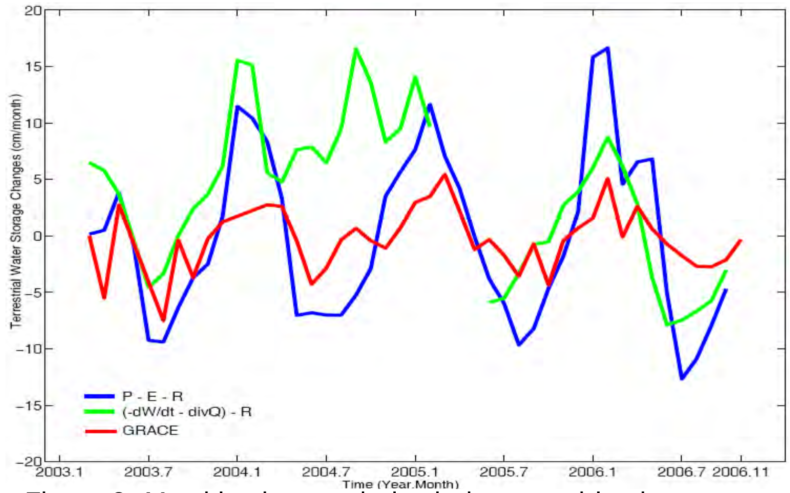

Figure 2. Monthly changes in basin integrated land water storage from GRACE (red), land-atmosphere water balance (green) and land water balance (blue).

While the WRC grant is modest, it has served an important purpose by giving our work focus on California and the west. It has allowed us to establish new collaborations and to make important progress towards our longer-term objectives 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 of *Yeh et al.* [2006] 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

Rodell, M., J. Chen, H. Kato, J. Famiglietti, J. Nigro and C. Wilson, Estimating ground water storage changes in the Mississippi river basin using GRACE, *Hydrogeology Journal*, doi 10.1007/s10040-006-0103-7

Swenson, S., J. Famiglietti J. Basara and J. Wahr, Estimating profile soil moisture and groundwater storage in the southern Great Plains using GRACE satellite gravimetric and Oklahoma mesonet soil moisture data, *Wat. Resour. Res.*, in press.

Yeh, P. J.-F., S. C. Swenson, J. S. Famiglietti and M. Rodell, Remote sensing of groundwater storage changes in Illinois using the Gravity Recovery and Climate Experiment (GRACE), *Water Resour. Res.*, 42, W12203, doi:10.1029/2006WR005374.

Professional Presentations

Dozier, J., J. Famiglietti, R. Rice. N. Molotch, T. Painter, and R. Bales, Analysis of the Sierra Nevada Snowpack in the 21st Century, AGU Fall Meeting, San Francisco, CA, December 10 - 14, 2007

Collaborative Efforts

We are working with Jeff Dozier from UCSB on GRACE-snow relationships. Work on objective 5, is just beginning in conjunction with Norm Miller at LLBL. With funding from LLBL, we will use GRACE for groundwater remote sensing of the Central Valley aquifer.

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Investigation of Groundwater Flow in Foothill and Mountain Regions using Heat Flow Measurements

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Temperature in the shallow and deep subsurface was measured at numerous locations in the Tahoe Basin region, using monitoring devices buried in the soil and high-resolution thermometers lowered down wells. A wide range of soil temperatures and well temperature profiles were observed, which are coupled to areal differences in subsurface heat and groundwater flow. Results indicate that infiltration in the mountain-block and at the mountain-front contributes significantly to recharge of adjacent valley aquifers.

The purpose of this investigation is to improve understanding of groundwater flow patterns in the Sierra Nevada and adjacent foothills, including bedrock infiltration and the role of upland bedrock areas in recharge of adjacent valley basin-fill aquifers. As human population and use of groundwater in the Sierra Nevada area continues to increase, protection of groundwater resources from contamination and general management of water resources can benefit from improved knowledge of groundwater flow patterns.

We have measured subsurface temperatures in the Tahoe Basin region, and are using patterns of subsurface heat flow to help trace groundwater flow. This is a well-established technique in hydrogeology, and has been used in many parts of the world to help define regional groundwater flow patterns and quantify the rates of groundwater flow into or out from overlying streams. Measurement of subsurface temperature profiles is relatively quick and inexpensive where accessible wells are located, consisting simply of lowering a high-resolution thermometer down each well and recording temperature measurements at every few feet of depth. Standard geophysical techniques for characterizing aquifers, such as ground-penetrating radar and seismic, are expensive and not applicable in areas of shallow granitic bedrock typical throughout much of the Sierra Nevada.

Measured differences in subsurface temperature define subsurface conductive heat flow, which is typically perturbed by moving groundwater carrying heat energy as it flows. Thermal and hydraulic data used together can generally yield more accurate knowledge both of heat flow and of groundwater flow patterns than is attainable using thermal and hydraulic data separately.

Soils did not freeze at any of more than 90 monitored sites up to elevations as high as 7600 ft above mean sea level during the winter of 2004-05. Thus, infiltration during spring snowmelt was not impeded by a layer of frozen topsoil. During the warm season, soil temperature (T) is very sensitive to vegetative cover (Figure 1).

Many well T-profiles showed evidence of surface warming propagation to moderate depth, attributable to gradual air temperature warming that has been documented in the Sierra Nevada over the past several decades, and also to removal of vegetative cover at several sites. Depth intervals in many wells were isothermal, indicating that each of these boreholes served as a conduit for rapid vertical intra-borehole flow of groundwater within clearly-defined depth intervals.

For wells emplaced deep into granitic bedrock above valley areas, drilling records indicate the water table dropped substantially as drilling progressed, indicating large downward hydraulic gradients. This is consistent with conceptual and field studies in other areas showing that areas of high relief tend to promote groundwater flow to great depths. Standard hydraulic tests

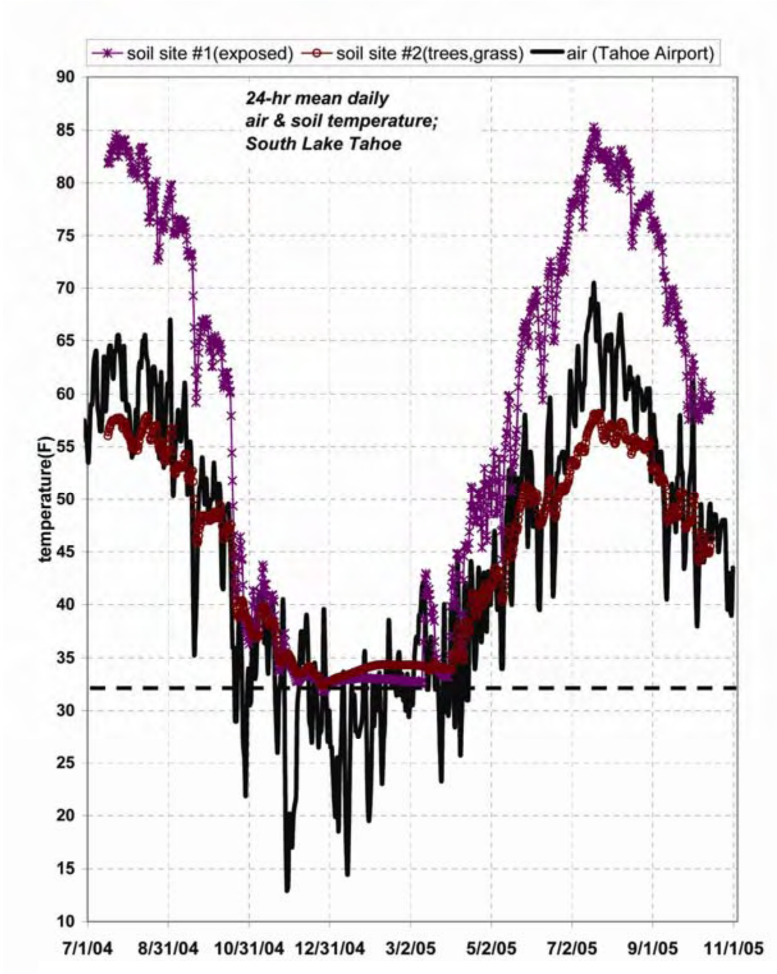

Figure 1. Daily mean air temperature (T) at the South Tahoe Airport, and daily mean soil T (at 6 inch depth) measured at two adjacent sites, from July 2004 to October 2005.

showed that horizontal permeability of bedrock spans a range previously reported for granitic rock in the Sierra Nevada. T-profiles are related to vertical recharge rate to depth in bedrock, and thus to vertical permeability, and show a very wide range between different areas.

At several bedrock wells, temperature measurements yield constraints on estimates of the rate of groundwater flow downward beneath the borehole bottom. For some valley wells completed in sediment, the presence of groundwater discharging upward from the bedrock to the sediments is indicated by abnormally large T-gradients. The origin of bedrock discharge up into overlying sedimentary valley aquifers is recharge and deep percolation into bordering mountain block areas thru fault zones and intersecting permeable joint sets. Areal and regional thermal springs are direct evidence for such deep bedrock flow. Other bedrock springs might discharge and disperse undetected beneath areas of valley-fill sediments.

Within valley aquifers, the T-profiles of some wells are related to mean annual rates of infiltration of precipitation and mean annual rates of aquitard leakage. Marked temperature inversions were observed at several wells, showing the presence of rapid lateral flow of cool groundwater, consistent with intensive recharge at mountain-fronts that border valley areas.

Collaborative Efforts

Ivo Bergsohn (South Tahoe PUD hydrogeologist; P.G., C. Hg.), and Dr. Eric Labolle (Project Scientist, UC Davis) have developed hydrostratigraphic and calibrated 3-D groundwater flow models of the South Tahoe basin-fill aquifer system. We have initiated evaluation of the consistency of groundwater flow model results and stable isotope data with results for heat flow analyses in the South Tahoe area.

We have also initiated a collaborative effort with regard to analysis and areal extrapolation of the soil temperature data set. In addition to use of this data in our research, pertinence to Sierra Nevada ecosystem change research and montane micrometeorology is being explored by Dr. James H. Thorne and Jonathon Greenburg of UC Davis, and Dr. Solomon Dobrowski of the University of Montana.

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Predicting the Impacts of Urbanization on Basin-scale Runoff and Infiltration in Semi-arid Regions

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Water resources in semi-arid regions are threatened by rapid and extensive urbanization. This is particularly evident in southern California where expansion of impervious surfaces covers large areas, influencing recharge and percolation to regional aquifers as well as flooding and streamflow patterns. The goal of this study is to provide improved understanding of the impacts of rapid urbanization on semi-arid watershed processes and provide relevant information for decision-makers on alternative land-cover patterns.

Urbanization has been shown to impact both surface water and groundwater quality and quantity. However, the majority of studies addressing urbanization and the related impacts on water resources are undertaken in humid regions. This research will provide a better understanding of the impacts of urbanization on hydrologic processes in semi-arid regions, as well as provide a platform for the discussion of alternative urban forms and development locations to mitigate anticipated deleterious impacts. This study addresses several key science questions, including: 1) What are the current dynamics in a rapidly urbanizing watershed (runoff, streamflow patterns and infiltration rates)? 2) Can a semi-distributed, basin-scale model, using high-resolution satellite-based products, adequately simulate current watershed dynamics? 3) Can this detailed basin-scale model predict the impacts of proposed urban developments and reduce the uncertainty in the watershed response? and finally, 4) Can results from this study be used by decision-makers as they proceed with development in the rapidly urbanizing regions?

We have selected the upper portion of the Santa Clara River (SCR) as the primary study area. This 640 mi^2 semi-arid region, located 30 miles north of the city of Los Angeles, is in the transition from a natural to an urbanized state. Population in the basin is expected to increase from a population of 213,000 (2000 census) to 350,000 in the year 2025 (SCAG, 2000). The basin consists primarily of natural vegetation (chaparral, sage and grasslands), with concentrated urban and residential lands near the outlet along the Santa Clarita-Valencia corridor. The Santa Clara watershed supports a series of groundwater basins within the floodplain regions along the river. The selected study area is comprised of two primary groundwater basins, the Acton Valley Basin (12.9 mi^2) and the SCR Valley Basin (103 mi^2). The ongoing development provides a unique opportunity to evaluate the effects of urbanization on basin-scale hydrological processes in near-real time.

We have employed the Hydrological Simulation Program---Fortran (HSPF) (USEPA Model) to simulate watershed dynamics across a range of temporal scales. The model has been extensively used in water management and land use studies across the United States. The HSPF has more recently been applied to two watersheds in Los Angeles County to address urbanization-related changes in streamflow patterns. In addition, the model includes water quality and sediment transport modules which we plan to use for further work in the Santa Clara basin. Historical hydrological data including rainfall (from 15 rain gauges maintained by the LADPW) and streamflow (from 6 gauges maintained by the USGS) data for the SCR have been collected. Investigation of these data sets reveals that rainfall over the study area shows no significant trend while streamflow runoff shows a slightly increasing trend ($s=0.018$, $p<0.001$) over the past 40 years. We have also collected and processed relevant land use, soil, topography and potential evapotranspiration data for the basin. The model has been initialized and baseline simulations (without calibration) have been run for the upper Santa Clara. A detailed sensitivity analysis has been completed which will allow us to focus on calibration of relevant parameters.

Year 2 Plans

Calibration and validation of the model under current land cover conditions is ongoing and will be finalized. Various land-cover scenarios will be developed and modeled to predict the impact of development patterns on watershed processes. We will also investigate the impacts of various climate trends on watershed processes (with and without land cover change) to help identify the potential impacts of each signal (urbanization and climate variability) on the Santa Clara system.

Professional Presentations

Hogue, T.S., Improving the Understanding and Prediction of Hydrologic Processes in Altered Landscapes, Invited Talk - CEA-CREST (NSF Center for Environmental Analysis-Centers of Research Excellence in Science and Technology), California State University, Los Angeles, January, 2007.

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Ecohydrologic Effects of Stream Restoration

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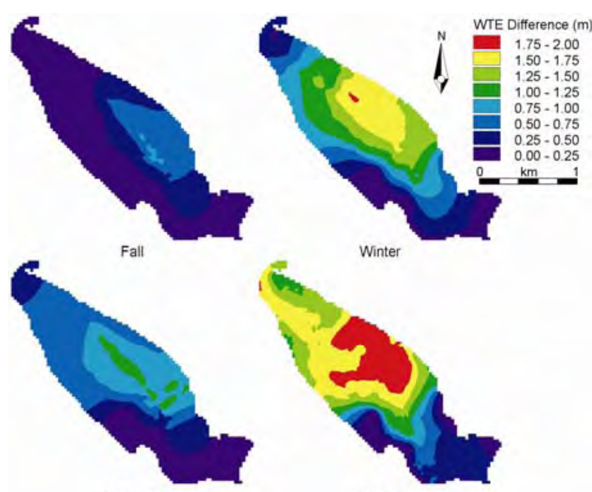
Stream restoration activities throughout California are numerous; however the hydrologic and vegetative responses of these restored systems are poorly understood and rarely documented. The goal of this research is to quantify the hydrologic and ecologic effects of a "pond and plug" stream restoration 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 led 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 understanding of the ecohydrologic effects of stream manipulation is vital in improving 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 and involves the linkage of 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, calibrated and validated. 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 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, including stream flow and water table elevation monitoring, geochemical boundary condition characterization, and refinement of the post-restoration digital elevation model. During the second year, we calibrated and validated the hydrologic model, then applied the model to simulate the pre- and post-restoration scenarios by



Difference of water table elevation as modeled in pre- and post-restoration scenarios.

altering the floodplain topography and stream channel networks. Our modeling results document three general hydrological responses to the meadow restoration effort: 1) increased groundwater levels and volume of sub-surface storage; 2) increased frequency/duration of floodplain inundation and decreased magnitude of flood peaks; and 3) decreased annual runoff and duration of baseflow. This study supports and quantifies the hypothesis that "pond and plug" type stream restoration projects have the capacity to re-establish hydrological processes necessary to sustain riparian systems.

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 was analyzed and several communities (*Poa pratensis / Bromus japonicus, Carex nebrascensis / Juncus balticus, Downingia bacigalupii / Psilocarphus brevissimus, and Eleocharis macrostachya / Eleocharis acicularis*) identified. Each of these vegetation communities was related to the minimum and average growing season depth to groundwater using direct gradient analysis. In addition, common herbaceous plant species native to meadows in California, were also individually related to growing season water table depth variables. Using these data, a predictive vegetation model statistically linking these identified plant species and communities to the temporal trends in inundation and availability of shallow groundwater was developed. This model is currently being used in combination with the hydrologic model to simulate the areal extent of various vegetation communities present under pre- and post-restoration hydrologic conditions. Preliminary results indicate an increase in the distribution of wet and moist meadow species (e.g. *Carex nebrascensis, Juncus balticus, Juncus covillei, and Eleocharis* macrostachya) and a reduction of the species found at the drier end of the hydrologic gradient (e.g. *Aster occidentalis, Poa bulbosa, Leymus triticoides and Epilobium brachycarpum*), in addition to an increase in the habitat available for species specializing in vernally wet environments (e.g. *Downingia bacigalupii, Psilocarphus brevissimus, Mimulus tricolor and Polygonum polygaloides)*.

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 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 a multitude of demands on water resources within the state continues to grow, a better understanding of the hydrologic and ecologic effects of such restoration activities is crucial.

Publications

Hammersmark, C.T., M.C. Rains, and J.F. Mount. In press. Quantifying the Hydrological Effects of Stream Restoration in a Montane Meadow, Northern California, USA. *River Research and Applications.*

Professional Presentations

Hammersmark, Christopher, Mark Rains and Jeffrey Mount, Hydrologic Effects of a Pond and Plug Stream Restoration in a Mountain Meadow, 2007 Society of Wetland Scientists International Conference, Sacramento, CA, June 2007.

Hammersmark, Christopher, Mark Rains and Jeffrey Mount, Quantifying the Hydrologic Effects of Stream Restoration in a Mountain Meadow, Floodplain Management Association 2007 Annual Conference, South Lake Tahoe, NV, September 2007.

Collaborative Efforts

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Investigating Large Woody Materials to Aid River Rehabilitation in a Regulated California River

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To aid in management and rehabilitation of regulated rivers in the Mediterranean climate of California, it is necessary to understand in-channel large wood processes at the habitat unit, reach, and watershed scales. Field work conducted at each scale has helped to develop a conceptual model of wood dynamics for use in decision-making processes.

Few river rehabilitation projects have used large woody materials (LWM) as a tool for improving salmonid habitat, and there is little science to guide the enhancement or placement of LWM. This research is investigating the role of LWM in the Mediterranean climate zone of California, in order to develop a scientific conceptual model of LWM dynamics for regulated rivers in the region and a decision-making framework that will enable river managers to include scientifically based LWM structures into rehabilitation designs, thereby enhancing stream complexity and habitat diversity, and creating robust ecosystem health.

(1) To obtain insight into LWM dynamics in regulated rivers, data on large wood (>1 m length, >10 cm diameter) attributes, including wood piece length, diameter, and decay condition, were collected from the 7.6 km reach between Camanche Dam fish fence and Mackville Road Bridge on the Mokelumne River, CA between September 2006 and March 2007. Hydraulic habitat units were identified and mapped based on velocity and depth measurements. The first kilometer of the reach was surveyed for riparian corridor recruitment potential. Fall-run Chinook salmon redd locations were recorded by East Bay Municipal Utilities District (EMBUD) biologists. A GIS database of all LWM hydraulic structures, geomorphic channel characteristics, and redd locations for the 2006-2007 field season has been produced using ESRI's Arc9.

(2) In order to create hydraulic complexity, a logjam of 30 logs with length > 5 m and diameter > 30 cm was built on the Mokelumne River, 500 m downstream of Camanche Dam fish fence in September 2007, in conjunction with EBMUD biologists. Materials used to build the logjam were obtained from the local riparian corridor; a number of dead alders along the channel and a few living oak branches hanging over an adjacent trail were cut down for use in the project. Existing wood structures present in the channel and on the bank at water's edge were used as linchpins for the jam. Imported boulders and gravel were used as ballast; no cables or other non-natural tie-downs were used. This logjam will be monitored for signs of individual wood piece movement as flows vary, and for its use by various salmonid and other aquatic species life stages.

LWM measurements on the lower Mokelumne River.

(3) To develop a model of LWM dynamics above reservoirs, fieldwork in summer 2006 was conducted in Pardee Reservoir on the Mokelumne River, Bullard's Bar on the Yuba, Oroville on the Feather, Folsom on the American, and Don Pedro on the Tuolumne. Quantification of LWM that originated in the upper watershed and traveled into the reservoirs during high precipitation and snow-melt events in water year 2005-2006, was done using a helium filled blimp with attached camera to obtain aerial photographs. We aim to develop a conceptual model of wood flux into reservoirs based on wood recruitment potential, flow rates into reservoirs, and significant upper watershed precipitation events (rainfall intensity, duration, and frequency) events.

Key findings: (1) Using the non-parametric Kolmogorov-Smirnov test, there were no significant differences in LWM presence across all habitats (riffle, run, glide, pool) in the 7.5 km reach directly below Camanche Dam on the Mokelumne River, thus LWM density distribution was statistically indistinguishable throughout the study reach. There were significant differences in redd density between riffles and all other habitats, but no significant difference in redd density between runs and glides. Pools were not tested since no redds were recorded in pools. These results suggest that salmon preferentially use riffle habitat to build redds, while runs and glides are used secondarily. Using the non-parametric Wilcoxon rank sums test, wood densities were significantly different than redd densities in riffles and runs, but not significantly different in glides. These findings suggest that LWM is important to salmonid redd locations in marginal hydraulic habitat zones such as glides, where lower velocities may preclude these areas from use for redd building without LWM presence to create hydraulic variability. (2) It is feasible to build logjams using local riparian corridor trees. Existing structural elements play an important role by serving as linchpins for building the jam. (3) Wood accumulations in reservoirs are subject to watershed scale processes that should be predictable based on a few variables: watershed hydrograph, forest condition, and years since last large runoff year.

We expect to use the final year of this grant to develop a PhD proposal to identify causal natural and anthropogenic factors in LWM supply and fate at the basin scale.

Professional Presentations

Senter, Anne E. and G.B. Pasternack, Investigating the Geomorphic and Ecologic Functions of Wood in Relationship to Habitat Type and Salmonid Redds on a Regulated California River, San Francisco, CA, American Geophysical Union, Dec. 2006

Collaborative Efforts

PI Greg Pasternack has collaborated with EBMUD extensively since 1999 on rehabilitation projects on the Mokelumne River below Camanche Dam. The LWM project funded by this grant was also funded in part by an EBMUD-affiliated grant. Dr. Joseph Merz, an EBMUD fisheries biologist extensively involved in the rehabilitation projects, has agreed to be a Master's committee member for Anne Senter.

Professor Herve' Piegay, a visiting scholar with expertise in physical wood processes from the Center for National Research (CNRS-UMR) in France, accompanied the researchers into the upper Mokelumne River watershed in July 2007 to discuss research approaches to wood flux across the Sierra, wood recruitment potential in individual watersheds, physical processes associated with wood movement and variable flows, and identification methods to determine transport distance and physical breakdown patterns.

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The Influence of Groundwater Depth and Nutrient Limitation on Plant Water Use in Owens Valley, California

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While previous studies in Owens Valley have focused largely on the direct effects of groundwater depth on plant water stress as a control on plant community composition, particularly the abundance of grasses vs. shrubs, our results suggest that indirect effects of declining soil moisture on soil N availability are a key control. The interactions between water and N cycles may play a primary role in influencing vegetation dynamics in shallow groundwater ecosystems such as in the central Owens Valley, and should be considered in projections of the effects of water extraction and redistribution on plant communities.

Owens Valley, California is a closed hydrologic basin at the base of the Sierra Nevada Mountains. In 1913, the Los Angeles Department of Water and Power (LADWP) began diverting water from this semi-arid basin, which supports vegetation from both the Great Basin and the Mojave Deserts. Despite several decades of water management and monitoring in the valley, the current and potential impacts of water redistribution on local vegetation and ecosystem processes remain highly uncertain, in part due to a limited understanding of the interactions between vegetation dynamics and hydrology. In this study, we evaluated species differences in plant water and nitrogen sources to explore potential drivers of the success of grass and shrub functional types within the central Owens Valley. The study focused on three sites with shallow groundwater, generally within 3 m of the surface, but with varying community composition. Plant water sources were identified with measurements of the isotopic composition of plant water, soil water, and groundwater. Ecosystem nitrogen (N) cycling was evaluated with measurements of soil organic and inorganic N content, and plant and soil N content and isotopic composition. We also measured plant gas exchange and water potential (a measure of plant water stress), to determine the extent to which different species were water versus N limited. We found that shrub species generally utilized soil water from deeper sources than the grass species as indicated by greater isotopic enrichment (more water containing the heavy isotope ^{18}O) in the grasses. The isotopic composition of water in the shrub species indicated that shrubs largely utilized groundwater as a water source. This is consistent with the hypothesis that grasses are more sensitive to lowered water tables than shrubs. However, both grasses and shrubs showed little evidence of seasonal water stress. All species showed a decline in leaf N throughout the growing season which was consistent with a trend of decreasing plant available N in the soil. Losses of N during the growing season may be attributable to volatilization of N in gaseous form (eg. soil nitrous oxide and ammonia emissions) and to reduced microbial release of N in the shallow soil during progressive soil drying in summer. The decline in soil N influenced photosynthesis of the grass species *Distichilis spicata*. Photosynthesis of the shrub species *Atriplex torreyi* and *Ericameria nauseosa* remained relatively constant throughout the season and was not correlated with water sources, water potential, or leaf N. However, leaf N was significantly correlated with photosynthesis in *D. spicata* (Figure 1). Seasonal losses in soil inorganic N caused by declining surface soil moisture

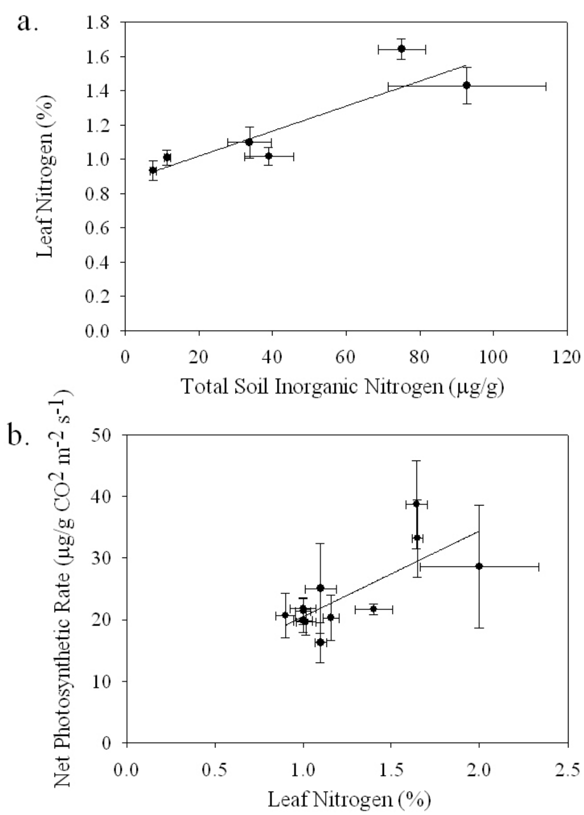

Figure 1. a) Leaf level photosynthesis versus percent leaf N for the grass species *Distichlis spicata* in both 2005 and 2006 (R^2=0.50, p<0.01). b) Percent leaf N versus total soil inorganic N for *D. spicata* in 2006 (R^2=0.71, p<0.05). Error bars show the standard error (n varies from 3-5 replicates).

appeared to largely explain seasonal declines in photosynthesis of this species. Transpiration showed a similar trend to photosynthesis, and was therefore limited by N availability for the grass species. Previously, seasonal declines in ecosystem gas exchange have been attributed largely to direct, water stress-related seasonal declines in soil moisture and the depth of the water table. Our results suggest that both the spatial and temporal variability of plant gas exchange of grasses was more strongly influenced by an indirect effect of declining soil moisture: reductions in inorganic, plant available soil N concentrations. While previous studies in Owens Valley have focused largely on groundwater depth as a control on species composition, particularly the abundance of grasses vs. shrubs, our results suggest that controls on N cycling are likely to be an important determinant of the distribution of grasses in this region. The interactions between water and nitrogen cycles may play a primary role in influencing vegetation dynamics in shallow groundwater ecosystems such as in the central Owens Valley, and should be considered in projections of the effects of water extraction and redistribution on plant communities.

Collaborative Efforts

We collaborated with Prof. Sharon Billings at the University of Kansas to obtain the soil inorganic N data for this study. In addition, the Los Angeles Department of Water Power helped us select our study sites and gave us permission to conduct this research on their property.

Professional Presentations

Goedhart C.M., D.E. Pataki, S.A. Billings. Controls on plant gas exchange across a grassland to shrubland gradient in Owens Valley, California. Ecological Society of America meeting, San Jose, CA, Aug. 2007.

Pataki, D.E., S.A. Billings, E. Naumburg, C. Goedhart. Water sources and nitrogen relations of grasses and shrubs in phreatophytic communities of the Great Basin Desert. (poster) Ecological Society of America meeting, San Jose, CA, Aug. 2007.

Goedhart C.M., D.E. Pataki, S.A. Billings. Controls on plant gas exchange across a grassland to shrubland gradient in Owens Valley, California. Annual Meeting of the Southern California Academy of Sciences, Fullerton, CA. June 2007.

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Research Category II

Aquatic Ecosystems

This category encompasses basic observational, analytical and theoretical assessments of aquatic environments and ecosystems that enhance effective utilization of water resources. 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; roles and effects of non-native species; and reconstruction ecology.

Metal Cycling and Bioavailability during Phytoplankton Blooms in South San Francisco Bay

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Environmental Toxicology
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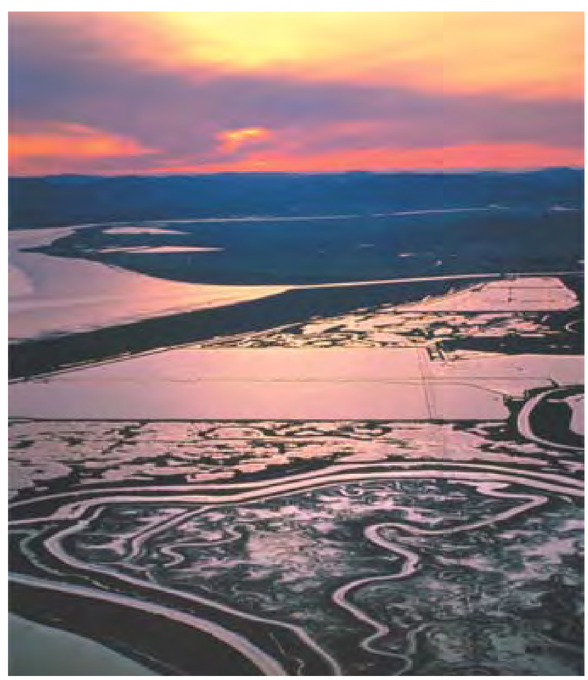
As the results of this study show, the relationships between algal blooms and trace metals in the San Francisco Bay are complex; algal blooms regulate some metal cycles and some metals regulate algal blooms. Consequently, natural or anthropogenic perturbations of either may directly impact the other and result in dramatic changes in the health of the estuary.

A series of studies on the interactions of trace metals and algal blooms in San Francisco Bay has been completed. The first of those studies showed that some dissolved metal concentrations (i.e., cobalt, manganese, nickel, lead, and zinc) decreased during an algal bloom, and then increased as the bloom decayed – releasing nutrients and metals back into the Bay waters. However, dissolved copper concentrations did not measurably change either during the bloom or its subsequent decay. This is notable because copper was once considered to be at toxic levels in Bay waters. Recent studies, however, have determined that most of that "dissolved" copper is strongly complexed with organic ligands and, therefore, not readily available to the plankton – either as a nutrient or as a toxicant. Our results corroborate that determination.

The second study showed that while total mercury concentrations in Bay waters are not measurably affected by algal blooms, concentrations of methylmercury are. This is notable because methylmercury is the form of mercury that is bioaccumulated to toxic levels in aquatic food chains. Consequently, algal blooms appear to increase the cycling of the toxic form of mercury in the Bay.

The third study showed that phytoplankton species changed during blooms. These changes may be partially due to changes in concentrations of some of the dissolved metals during that period. Conversely, changes in phytoplankton species during the blooms may account for some of the changes in dissolved metal concentrations during that period.

In summary, phytoplankton blooms have been shown to directly influence the concentrations of several metals in the Bay, but not copper – which was once thought to be limiting primary productivity in the Bay. The blooms also accelerate the cycling of methylmercury, which is magnified in fish to toxic levels in the Bay. Finally, metals may influence plankton species during a bloom.



Publications

Luengen, Allison, P. Raimondi, and R. Flegal. Contrasting biogeochemistry of six trace metals during the rise and decay of a spring phytoplankton bloom in San Francisco Bay, *Limnology and Oceanography*, 2007, 52(3): 1112-1130.

Professional Presentations

Flegal, Arthur R. Metals in San Francisco Bay. State of the Estuary, Berkeley, CA, October 2007.

Luengen, Allison, C. Conaway, and R. Flegal. Linking abiotic and biotic mercury reservoirs: Temporal trends and bloom dilution (invited presentation). San Francisco Estuary Institute Fourth Annual San Francisco Bay Mercury Coordination Meeting, Oakland, CA, February 22, 2007.

Luengen, Allison, N. Bloom, and R. Flegal. Mercury cycling during a spring phytoplankton bloom in San Francisco Bay (poster). Eighth International Conference on Mercury as a Global Pollutant. Madison, WI, August 2006.

Luengen, Allison and R. Flegal. Depletion of methyl mercury during a spring phytoplankton bloom in South San Francisco Bay. Northern California Chapter of the Society of Toxicology Spring Meeting, Half-Moon Bay, CA, April 2006.

Luengen, Allison and R. Flegal Interaction between nutrients, phytoplankton blooms, and mercury concentrations in San Francisco Bay. American Society of Limnology and Oceanography Ocean Sciences Meeting. Honolulu, HI, February 2006.

Collaborative Efforts

The research was conducted in collaboration with Dr. Jim Cloern and his colleagues with the United States Geological Survey (USGS). The samples were collected on a USGS research vessel during Cloern's cruises in the Bay, and USGS staff provided ancillary data (e.g., nutrient concentrations) and made the phytoplankton species counts utilized in the research.

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

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This project expands our knowledge of nitrogen cycling and processing in highly eutrophic estuaries of southern California. Field surveys show rates of nitrogen fixation are spatially and seasonally variable and could depend on both abiotic and biotic factors, especially nitrate levels in the water column.

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. This is especially important as urban development continues, though few functional coastal marshes remain in southern California. The remaining estuaries 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. 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, Sep. 2005, Feb. 2006, and Sep. 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.

All survey sites exhibited some nitrogen fixation activity, though it is clear that there is a great deal of spatial and temporal variability within the estuary. For most sites, activity was low relative to estuaries on the east coast of the United States. Though some sites exhibited higher nitrogen fixation rates, there does not appear to be a spatial or seasonal pattern. This indicates fixation is not simply related to seasonal or long-term site characteristics, and is more likely to be controlled by shorter-term sediment, water and biotic controls. 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

A student stands knee-deep in mud to collect algae for an experiment.

highest in areas with higher nitrate concentrations and higher organic material content.

Three field experiments were also performed. In July 2005 we executed a nutrient experiment to test the response of sediment nitrogen fixation and denitrification rates after exposure to nutrient enriched water treatments. This simulates estuary conditions as nutrient loading into the system continues to increase. Nitrogen fixation rates were significantly lower when overlying water contained higher nitrate concentrations, while the addition of phosphorus had no effect. Denitrification is expected to show increased rates with the addition of nitrate.

In July – August 2005 we performed a sediment transplant experiment to investigate how microbial nitrogen processing rates are affected by differences in sediment types. All sediment types showed an increase in nitrogen fixation rates when transplanted to a location where each received the same tidal flushing and exposure to water nutrients. Initial analysis indicated that this change coincided with a decrease in available water nitrate, and does not depend on sediment type. Denitrification is expected to decrease in these conditions.

In June – July 2006, a 40-day long field experiment investigated how the presence and density of green macroalgal mats, often a product of nutrient enrichment, affect nitrogen fixation and denitrification rates and other sediment and water characteristics beneath the algal mats. Initial results indicate that the presence of macroalgae did not affect nitrogen fixation rates, though fixation rates did change significantly over the course of the experiment. Further analysis will determine if the changes correlate with other abiotic characteristics. We predict the presence of macroalgae will affect denitrification.

This research contributes to our basic understanding of how nitrogen cycles through 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. Processes that add and remove nitrogen from estuarine ecosystems are especially important as nutrient loading and subsequent eutrophication will only increase in the future.

Selected Professional Presentations

Kane, Tonya and P. Fong. Sediment nitrogen fixation in Upper Newport Bay Estuary, southern California. California Estuarine Research Society Annual Meeting. Bodega, CA, March 2007.

Kane, Tonya and P. Fong. Quantifying rates and mechanisms controlling sediment nitrogen fixation and denitrification in a eutrophic estuary. Estuarine Research Federation Meeting. Providence, RI, November 2007.

Collaborative Efforts

Determination of nitrogen fixation and denitrification rates 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 for these measurements. He and members of his lab 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). A proposal has been funded by the San Diego Regional Water Quality Control Board to incorporate some of the questions we have been asking in 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 UCI'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.

The importance of wetlands is recognized by both scientists and the public, but understanding of the ecological processes that control the functioning of California wetlands is lacking. Economists estimate a hectare of wetland provides ~$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. We are working at UCI's San Joaquin Freshwater Marsh (SJFM) to better understand the biophysical and environmental controls on wetland carbon, energy and water vapor exchange. Located on the UCI campus, the SJFM is an 82-ha *Typha latifolia* and *Scirpus californicus* remnant of a large historical wetland.

Observations of the SJFM's carbon, energy, and water vapor exchange since 1999 demonstrate that these processes are highly variable from year to year. The observed interannual variability in carbon exchange from 1999-2003 was much greater than has been reported for other ecosystem types, such as tropical forests. The interannual variability at the SJFM is remarkable for two reasons: (1) the year-to-year shifts in carbon storage occurred despite similar environmental conditions between years and (2) the maximum rates of carbon uptake (Gross Ecosystem CO_2 Exchange, or GEE) were poorly correlated with ground based measures of green leaf area (Leaf Area Index, or LAI), but well correlated with remotely sensed surface greenness indices (the Enhanced Vegetation Index, or EVI; Figure 1). These results diverge markedly from previous ecological studies, which have demonstrated that: (1) year-to-year variation in carbon uptake is usually attributable to year-to-year variation in weather, and (2) year-to-year variation in

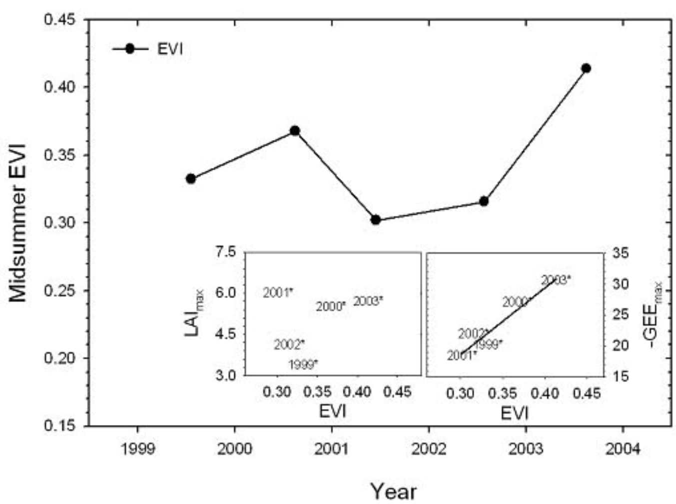

Figure 1. Midsummer Enhanced Vegetation Index (EVI) from 1999-2003. Relationship between green leaf area (LAI) and EVI (left inset plot) and relationship between EVI and maximum gross carbon uptake (GEE) (right inset plot). Symbols in inset plots are representative years.

carbon uptake is often associated with year-to-year variation in LAI, with greater CO_2 uptake during years with more leaves.

The SJFM is a highly productive ecosystem characterized by a large accumulation of litter. We hypothesized that standing litter from the previous year decouples the normal relationship between GEE and LAI by shading the green leaves and decreasing both GEE and EVI. We tested this hypothesis using small-scale manipulations of litter and measurements of EVI and chamber

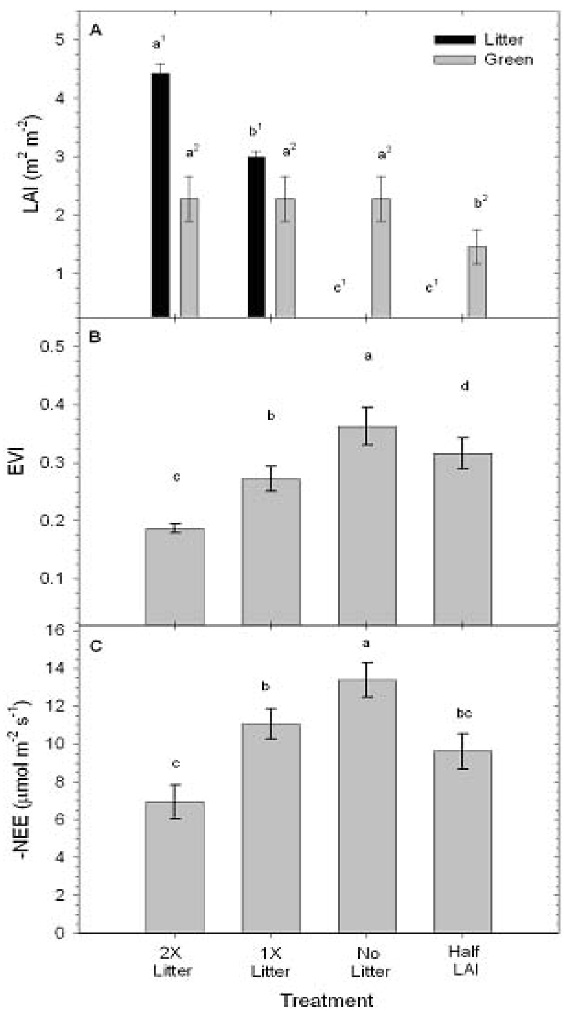

Figure 2. Average green leaf (Gray Bars) and litter (Dark Bars) area index [A], Enhanced Vegetation Index (EVI) [B], and Net Ecosystem Exchange of CO_2 (-NEE) [C] for each treatment. Error bars represent standard errors and different letters indicate significant differences at the 95% confidence level.

based CO_2 uptake (Net Ecosystem CO_2 Exchange, or NEE). EVI and chamber based NEE were measured after adding or reducing standing litter. Experimental manipulations supported our hypothesis by demonstrating that litter can confound the relationship between green leaf area, EVI, and NEE (Figure 2). Standing litter reduced EVI and NEE under constant green leaf area, resulting in poor relationships between green leaf area, EVI and NEE. Standing litter decreased NEE and EVI by 15 to 50%, which indicated that standing litter has a significant impact on the SJFM's carbon, energy, and water vapor exchange. Our work has implications for wetland restoration and wetland biogeochemical cycling and indicates that the link between productivity and carbon storage in freshwater systems is complex.

Publications

Goulden, M.L, M.E. Litvak, and S.D. Miller. Factors that control Typha marsh evapotranspiration. Aquatic Botany 86 (2007) 97–106.

Professional Presentations

Adrian V. Rocha and M.L. Goulden, Spatio-temporal variability in vegetation indices in a freshwater marsh and its implications for CO_2 exchange. American Geophysical Union, Fall 2006, San Francisco, CA.

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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Determining Factors for Eurasian Watermilfoil (*M. spicatum*) Spread in and around Lake Tahoe, CA-NV

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Invasive aquatic species pose serious ecological and economic threats to lakes, reservoirs and rivers. This study investigates vectors of introduction of aquatic nuisance species in California and Nevada's water bodies. Our findings show that lakes and reservoirs in California and Nevada are connected by way of recreational and transient boating, which is a major source of non-native species introductions.

Rivers, lakes and reservoirs are among the most invaded environments in the world; recreational boaters are a major source of non-native species introduction both within and between fresh water bodies. Boaters use California's waterways intensely, and create significant potential for the spread of non-native species such as Eurasian watermilfoil (*Myriophyllum spicatum*). New aquatic nuisance species (ANS) regularly appear in neighboring states, so California's waters are at constant risk of further invasion.

This research investigates patterns of Eurasian watermilfoil spread within Lake Tahoe, as well as to water bodies connected to Lake Tahoe via recreational boating. Lake Tahoe receives a high amount of boat traffic, and is centrally located in proximity to a number of popular lakes in California and Nevada. Eurasian watermilfoil is estimated to have arrived along the south shore of Lake Tahoe during the 1960's and has since spread to numerous locations around the lake.

We are exploring the following: (1) What are the processes of spread within a lake; i.e., is watermilfoil limited by available habitat or by dispersal mechanisms? (2) What other water bodies are Lake Tahoe boaters using? Do they act as potential sources of aquatic invasion? (3) Are there recognizable travel patterns for boaters in this region? What impact do these patterns have on invasion risk? (4) Are boaters aware of damages associated with invasive species?

During the 2005-2006 boating seasons approximately 800 boater interviews were carried out at 7 Lake Tahoe boat launch facilities. Information was collected regarding lakes visited before and to be visited after present use, travel within Lake Tahoe, invasive species awareness, boat cleaning habits, and vessel inspections for vegetation caught on boats and equipment. A survey of Lake Tahoe for Eurasian watermilfoil and Curly pondweed was carried out with the USDA Exotic and Invasive Plant Unit. Additionally, sediment and water quality testing of 13 popular boating destinations assessed habitat appropriateness for potential colonization. In 2007, similar sediment and water quality assessments were carried out at the top 10 visited water bodies in CA and NV as indicated by the 2005-06

Invasive plants like Eurasian watermilfoil easily get caught in propellers and engines. This boater pulled out a clump of plants that was clogging his intake at the Tahoe Keys Marina.

boater interviews. These assessments also included surveys for other high risk invaders such as the New Zealand Mudsnail, Quagga mussel, and Curly pondweed at lake access points.

Findings of these efforts include: Lake Tahoe boaters previously use lakes with known aquatic invaders; 15% of boats leaving Lake Tahoe carry fragments of invasive plant species on equipment; habitats within Lake Tahoe that are not yet invaded by Eurasian watermilfoil are not significantly different from those that are--suggesting that the invasion is still in progress; Eurasian watermilfoil and Curly-leaf pondweed continue to spread in Lake Tahoe; a majority of Lake Tahoe boaters *never* con-duct visual inspection of boats or boating equipment for ANS; a number of CA and NV lakes contain ANS that have not been previously discovered or reported. This information has been presented to homeowner's associations, science and management consortiums and published in local newspapers.

Moving forward, within-lake boater movement data will be combined with a 3-dimensional flow model designed by UC Davis researchers to understand dispersal mechanisms within Lake Tahoe. Sediment and water quality data collected for lakes other than Lake Tahoe will be analyzed to determine whether habitat or dispersal is the limiting factor for Eurasian watermilfoil invasion. These data are currently being used as the foundation for a multi-institutional collaborative proposal for a regional expansion of this study.

Graduate student Marion Wittmann collects some invasive Eurasian watermilfoil plants in North Lake Tahoe

Publications

Chandra, S. and Wittmann, M., 2007. *Invading Lake Tahoe: Dangers of invading organisms.* Keep Tahoe Blue News: Summer Newsletter: pg 2.

Professional Presentations

Wittmann, Marion E. *Pathways for Invasions by Aquatic Species*, Invasive Species Workshop, Incline Village, NV, May 2007.

Wittmann, Marion, E. *Boater mediated dispersal of Myriophyllum spicatum in CA-NV.* Western Aquatic Plant Management Society, San Diego, CA, March 2006.

Wittmann, Marion E., *Boater mediated dispersal of an invasive aquatic macrophyte, Eurasian Watermilfoil (Myriophyllum spicatum) in and around the Lake Tahoe Basin, CA-NV.* ESA Ecology in an Era of Globalization. Merida, MX, January 2006.

Collaborative Efforts

Researchers from the USDA Agricultural Research Service assisted with this study: Bob Blank (Soil Science Lab) provides sediment quality analysis; Lars Anderson (Aquatic Plant Research Lab) has provided survey data and culture tanks. The UC Davis--Tahoe Environmental Research Center provided data, facilities, field assistance, and instrumentation. UN Reno researchers provided field assistance.

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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 natural bacterial community in lakes throughout the region. Landscape analyses of fourteen lake chains have identified how bacterial communities change as water flows through catchments. Using this spatial survey approach, we have successfully defined linkages between bacterial species composition and a host of physical and chemical parameters, including catchment vegetation cover, elevation, and the composition of dissolved organic matter.

High-elevation lakes of the Sierra Nevada, once considered isolated from human impacts, are increasingly experiencing the effects of population expansion. 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 eradication of endangered species, alterations to algal productivity, and changes in zooplankton population dynamics. 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. 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.

Previous work in 2004-2006 characterized the phenology of microbial community structure and metabolism in Emerald Lake (Sequoia National Park). Results of that work indicated that snowmelt processes and seasonal flushing of dissolved organic matter played a key role in determining the species composition of bacteria in the lake. Bacterial metabolism was very variable and remained high year-round, even under the cover of snow and ice.

Steve Sadro and Craig Nelson filtering water for bacterial and solute analyses at Ediza Lake in September of 2006.

Work conducted in 2005 focused on assessment of the microbial response to predicted levels of atmospheric nutrient deposition. Experiments were conducted in Emerald Lake 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. A key result of this work was the finding that phosphorus clearly 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.

In 2006 a comprehensive survey of freshwater bacterial species and biogeochemical characteristics was carried out in fourteen lake-chains throughout the Sierra Nevada. Bacterial communities were found to closely track the composition of organic matter throughout catchments, which in turn was closely linked to vegetation cover and elevation. Results of this work have provided a comprehensive database of bacterial biogeography in Sierran lakes and demonstrated that 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, 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 2006 Summer Meeting, Victoria, BC, Canada, June 4-9.

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 California, Riverside, 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. This work has relied heavily on the cooperation of the USDA-Forest Service and the National Park Service, both through administrative support and the provision of key biological and geographic data sets.

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

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Three sediment resuspension models representing sediment characteristics were combined into a hydrodynamic and water quality model, DLM-WQ. The resulting models were applied to the Salton Sea, a shallow, wind-dominated, highly saline and eutrophic, terminal lake. The output of each water quality model is compared with measured data by using statistical and graphical evaluation methods. Based on these comparisons, DLM-WQ with an extended version of the García and Parker (1993) relationship gave the best match to the measured data. The resulting model simulation confirms that sediment resuspension is the most dominant process in the Salton Sea's nutrient cycling. The effect of proposed physical changes to the Salton Sea on water quality characteristics is presented.

The Salton Sea is a shallow, wind-dominated, terminal lake located in the southeastern desert of California (Figure 1). The Sea is a highly saline, eutrophic water body, characterized by high nutrient concentrations, high algal biomass as demonstrated by high chlorophyll *a* concentrations, high fish productivity, low clarity, frequent very low dissolved oxygen concentrations, massive fish kills, and noxious odors. However, the Salton Sea provides important habitat for large numbers of migratory bird species, of which some are threatened and some are endangered. Furthermore, sediment characteristics of the Sea (sediment cohesiveness in particular) are difficult to characterize as the sediments can exhibit a range of characteristics between cohesive and non-cohesive.

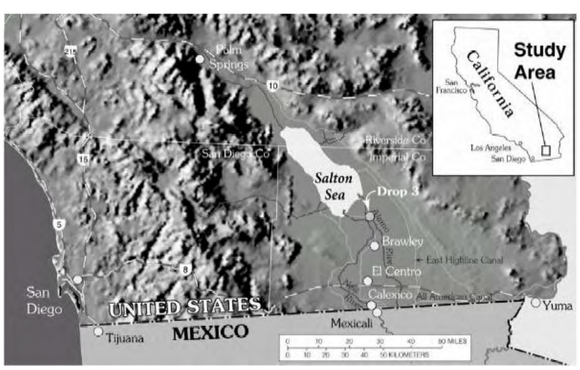

Figure 1. Salton Sea basin and surrounding area of California, U.S.A. and Mexico.

The physical size of the Sea will be significantly reduced in response to major inflow diversions that are planned under the Colorado River Quantification Settlement Agreement (QSA). The California Department of Water Resources (DWR) and California Department of Fish and Game (DFG) developed and proposed eight morphological alternatives to restore important ecological functions to the Salton Sea.

The relation between the sediment resuspension and the nutrient cycles of the Sea has been modeled by using a hydrodynamic and water quality model, Dynamic Lake Model – Water Quality (DLM–WQ), combined with the empirical sediment resuspension model of Somlyody (1986) which makes no provision for variable sediment characteristics.

In this research, we combined three other sediment resuspension models into DLM-WQ, and then applied them to the Salton Sea. The three sediment models represent different sediment characteristics, for example Mian and Yanful (2004), a linear relation between sediment erosion rate and suspended sediments for cohesive sediments and an extended relation of García and Parker for non-cohesive sediments.

The output of each water quality model is compared with measured data by using statistical and graphical evaluation methods. By these comparisons, DLM-WQ with the extended relation of García and Parker, originally developed for open channel flows, was considered the best model for resolving both the seasonal trends and the short-term variations of most water quality variables of the Salton Sea. The model simulation confirms that nutrients in both particulate and dissolved forms (from sediment pore-water) induced by sediment resuspension are presently the most important factor in the Sea's nutrient cycling.

To explore the effect of changes of morphology on the water quality of a future Salton Sea, we selected two of the alternatives that have been proposed by DWR and DFG for the Salton Sea: the North Sea Combined and South Sea Combined (see Figure 2). The DLM–WQ, with the extended formula of García and Parker, was employed to simulate water quality characteristics of these two alternatives. In both alternatives, the anoxia in the hypolimnion in the summer would be spatially and temporally increased due to an increase in the length of the stratification period, during which toxic substances and organic materials could accumulate in the sediments.

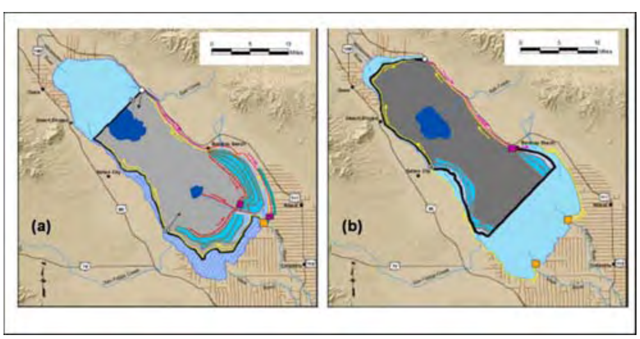

Figure 2. Two alternatives proposed for a future Salton Sea by DWR and DFG: (a) North Sea; (b) South Sea.

Publications

Chung, E. G., F. Bombardelli, S. G. Schladow, 2007. Modeling Linkages between Sediment Resuspension and Water Quality in a Shallow, Eutrophic Lake: Statistical Comparison of Sediment Resuspension Models. *Ecological Modeling,* submitted.

Chung, E. G., F. Bombardelli, S. G. Schladow, 2007. Sediment Resuspension in a Shallow Lake. *Water Resources Research*, submitted.

Chung, E. G., S. G. Schladow, J. Perez-Losada, D. M. Robertson, 2007. A Linked Hydrodynamic and Water Quality Model for the Salton Sea. *Hydrobiologia*. In press.

Selected Professional Presentation

Chung. E.G., F.A. Bombardelli, and S.G. Schladow. 2007. Influence of sediment resuspension in a shallow, eutrophic lake. The Fifth International Symposium on Environmental Hydraulics. University of Arizona, Tempe, AZ.

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 agencies, as well as staff from the California Department of Fish and Game. We are also collaborating with the USGS and NASA on Salton Sea related issues. We have also established an ongoing collaboration with Dr. Francisco Rueda of the University of Granada, Spain.

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Control of Mercury Methylation in Wetlands through Iron Addition

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To restore aquatic habitat, significant effort is being directed to the restoration of wetlands. However, wetland restoration can exacerbate mercury bioaccumulation in fish and wildlife by providing an environment that is conducive to mercury methylation. This project is investigating the potential for decreasing mercury methylation by amending wetland sediments with iron.

Methylmercury (MeHg) is a potent neurontoxin that affects both human health and wildlife, and its formation in the anoxic sediments of wetlands has led to mercury contamination in aquatic ecosystems. Elevated levels of mercury, which exists primarily as MeHg in biota, are responsible for over 75% of the fish consumption advisories issued in the United States. Mercury is of special concern in California due to elevated concentrations caused by historical mining practices. The primary objective of this research project is to develop a novel method of restoring and constructing wetlands that will minimize MeHg production in wetland sediments without sacrificing natural habitat potential.

Since the 1780's, California has lost an estimated 91% of its wetland acreage, and it has only been over the past few decades that policy and management decisions have been made to reverse this trend (e.g., the proposed restoration of over 15,000 acres of salt marsh within the San Francisco Bay). Wetlands are extremely beneficial ecosystems to California as they serve as essential habitat for a variety of wildlife species, including the federally endangered California clapper rail, offer flood protection, and improve water quality. However, wetlands support high levels of MeHg production, and as a result, the restoration of these essential habitats may exacerbate the mercury problems that already exist within the food web.

This project is studying a method of reducing mercury methylation rates by addition of ferrous iron to wetland sediments to control the availability of sulfide. As sulfide concentrations decrease, sulfate-reducing bacteria produce less MeHg because the concentration of dissolved, bioavailable mercury decreases. In a previous research project, we showed that this approach decreases net MeHg production in sediment slurry systems. This project will test the efficacy of iron addition under conditions more closely approximating those encountered in wetlands using laboratory microcosms collected from tidally influenced estuarine wetlands around the San Francisco Bay. In addition to studying the effect of the iron amendment on MeHg production, we are also evaluating the role that certain species of wetland plants play in MeHg production by altering the conditions of the sediments surrounding their roots, and how plant/sediment interactions are affected by iron amendment. The results of this study will determine if an iron amendment has the potential to be an effective control of MeHg production in wetlands, as well as to illustrate if certain plant species can be selected for in the restoration of wetlands to help reduce the potential exacerbation of the MeHg problem.

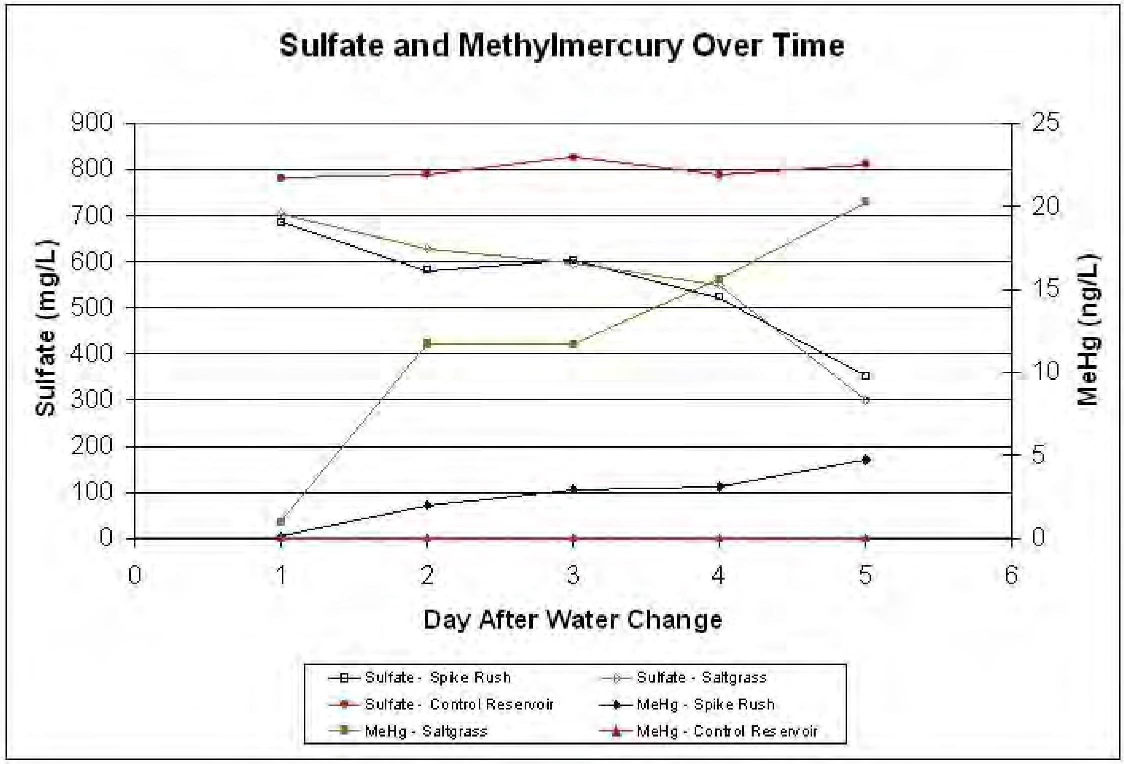

Figure 1: Relationship between sulfate reduction and methylmercury concentrations in wetland microcosms. These data indicate a strong relationship between the activity of sulfate-reducing bacteria and the production and export of methylmercury.

During the first year of the project, a microcosm system was designed and tested under operating conditions that simulate tidal cycles. Two potential field sites were identified and sediment cores with intact plant systems were collected for the microcosms. Pickleweed (*Salicornia virginica*), a halophytic salt-marsh plant that will serve as our initial species of interest, was collected from the tidally influenced high marsh plain of the Gambinini Marsh site along the Petaluma River in Sonoma county. Two additional plant species (saltgrass and a spike rush) were collected from Lower Joyce Island in the Suisun Resource Conservation District. The microcosms were grown and monitored over time for a variety of chemical parameters. These preliminary studies indicate that the microcosm system is able to support plant growth and an active sulfate-reducing microbial community, which is capable of producing substantial quantities of MeHg (Figure 1). The full-scale system of 12 pickleweed microcosms collected from Gambinini Marsh will go online during late summer 2007. After the completion of these experiments, we will conduct similar studies using different wetland plant species common to the tidal marshes of San Francisco Bay, such as saltgrass (*Distichlis spicata*) and cordgrass (*Spartina* spp.), to evaluate their individual effects on MeHg production relative to their controls without above-ground vegetation and in comparison to the effect of pickleweed.

Collaborative Efforts

Mark Marvin-DiPasquale, of the USGS, is collaborating with us on experimental design and interpretation of data.

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Restoring Rangeland Watersheds & Fisheries: Pine Creek Watershed & Eagle Lake Rainbow Trout

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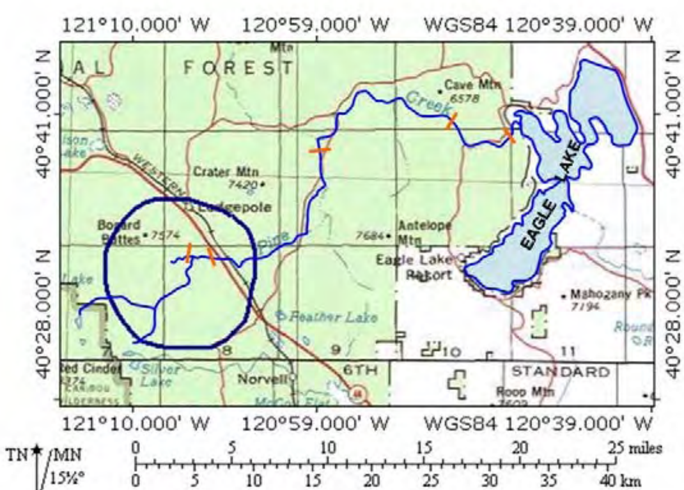
This is the first year of a study to test whether the numerous watershed restoration activities conducted during a 20-year effort in the Pine Creek watershed (Lassen County) have provided conditions under which Eagle Lake rainbow trout can complete their natural life cycle.

The purpose of this project is to test whether the numerous watershed restoration activities conducted during a 20-year effort in the Pine Creek watershed have provided conditions under which a proportion of Eagle Lake rainbow trout (ELRT, *Oncorhynchus mykiss aquilarum*), a Species of Special Concern, can complete their natural life cycle. Results from this project will help us to answer the question, for this and other rangeland watersheds, "How much restoration is enough?" Pine Creek watershed has historically provided critical spawning and rearing habitat for the ELRT. Over the past 100+ years, modification of Pine Creek and its watershed has resulted in the decoupling of the ELRT from its native stream habitat, and barriers have prevented ELRT from attempting their natural spawning migration of over 20 miles. The fishery is now supported entirely by hatchery production.



Map of Eagle Lake and Pine Creek watershed showing PIT antenna locations (orange bars). The upper watershed, where Eagle Lake rainbow trout may spawn, is indicated by a blue circle.

The approach we are taking is a comparative field survey including habitat, and fish migration and rearing, followed by a stakeholder workshop to share the new information. We are working at a watershed scale to determine the management actions necessary for the restoration of spawning and rearing of ELRT. Our main objectives are to: (1) Track the upstream migration of ELRT spawners from the mouth of Pine Creek, and relate movement to environmental factors such as water temperature and flow, and (2) Test the ability of ELRT to spawn and rear in Bogard Spring Creek, a tributary of Pine Creek, following temporary removal of brook trout, non-native fish that prey upon juvenile ELRT.

In 2007 we conducted a habitat survey to determine conditions during ELRT spawning migration, spawning, and rearing. We sampled 9 monitoring stations monthly from spring to fall for in-stream physical habitat, flow, temperature, dissolved oxygen, overhead cover, spawning substrate size, and water transparency and quality. In spring 2008 we will use passive integrated transponder (PIT) antennas to track the upstream movement of ELRT spawners, and relate this to environmental factors (flows in 2007 were very low and precluded this part of the study). We will capture a sample of ELRT at the barrier near the mouth of Pine

Creek during the spring spawning migration period. A sample of 100 fish, spread out over the time span of the spawning run, will be anesthetized and surgically implanted with PIT tags. After a recovery period, fish will be released upstream of the passage barrier. Upstream migration of ELRT will be monitored in the lower, middle and upper sections of Pine Creek with channel-spanning stationary PIT antennas. Water and air temperature will be monitored with loggers near the passage barrier on lower Pine Creek, in spawning habitat in upper Pine Creek, and at antenna sites along the length of Pine Creek. Flow will be measured weekly during the spring migration period at a fixed location in lower Pine Creek.

Tagged Eagle Lake rainbow trout spawner.

We are also studying the rearing of ELRT juveniles with and without non-native brook trout in the spawning and rearing habitat of the upper Pine Creek watershed, and testing methods to decrease the competition and predation that juvenile ELRT face from brook trout. In spring 2007 we conducted a pilot test in which we transported a small sample of PIT tagged ELRT spawners to the upper Pine Creek watershed to allow them to spawn. In 2008 we will transport 100 PIT tagged ELRT spawners to the upper watershed to allow them to spawn in Bogard Spring Creek and a comparison area, the mainstem reach of Pine Creek near Stephen's Meadows. In August 2007 we electrofished all of Bogard Spring Creek to decrease the density of brook trout. We will conduct summer snorkel surveys of Bogard Spring Creek and the non-electrofished mainstem reach of Pine Creek to determine the spawning and rearing success of ELRT in relation to the electrofishing treatment.

The results of this study will assist resource agencies to determine the management

PIT antenna installed in the upper watershed.

actions necessary to restore natural spawning and rearing of ELRT, and to sustain the trophy ELRT fishery and the economic benefits it provides to Lassen County.

Professional Presentations

Thompson, Lisa, Gerard Carmona Catot, Teresa Pustejovsky, David Lile, Peter Moyle, & Kenneth Tate. Restoring Pine Creek Watershed & Eagle Lake Rainbow Trout. American Fisheries Society Conference, San Francisco, CA. Sept. 4, 2007.

Collaborative Efforts

This project involves and expands on existing relationships with collaborators including the Pine Creek Coordinated Resources Management Planning Group (CRMP), California Department of Fish and Game, US Forest Service, Natural Resource Conservation Service, Susanville Indian Rancheria, and numerous volunteers. These groups made extensive in-kind contributions of time volunteered on field work. US Forest Service staff assisted in determining locations for PIT antennas, and supplied, installed, and monitored water temperature loggers along the length of Pine Creek. Mr. Kerry Mauro (Mauro Engineering, Mount Shasta, CA) constructed PIT antennas on a pro bono basis, for a substantial cost savings.

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Research Category III

Water Quality

Research in this category encompasses all aspects of water quality management. Topics include the sources and nature of contamination; effects of contamination on human health, plants 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.

Anaerobic Microbial Debromination of Polybrominated Diphenyl Ethers (PBDEs)

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The purpose of this research is to understand how microorganisms in the environment might transform the toxic polybrominated diphenyl ethers (PBDEs). We found that anaerobic bacteria can remove bromines from the molecule, creating potentially more toxic less brominated PBDEs. We are currently testing the ability of aerobic bacteria to breakdown the byproducts of anaerobic debromination.

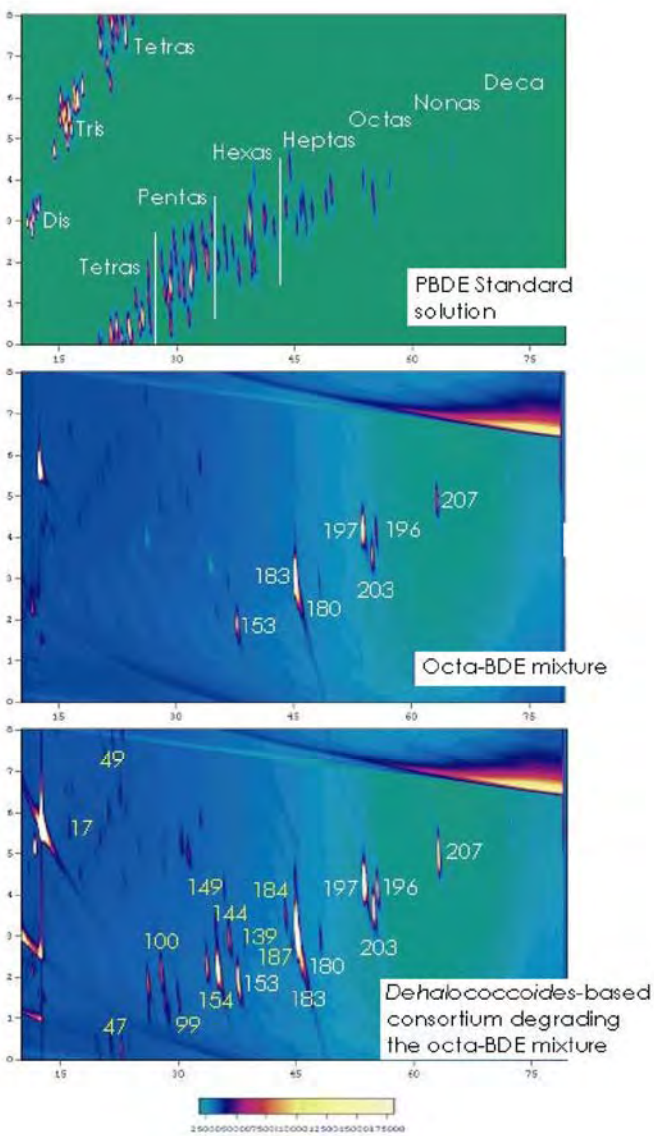
Polybrominated diphenyl ethers (PBDEs) are flame retardants that have been used for three decades in a wide variety of manufactured materials. The PBDE family comprises 209 different compounds, or congeners, that have different chemical and toxicological properties. Recent discoveries of the endocrine-disrupting ability of some of these compounds as well as exponentially increasing human breast-milk concentrations have raised concern about their use and have lead to regulatory bans for some of the compounds in California.

Anaerobic dehalogenating microorganisms are capable of removing halogens from a variety of compounds. Given that the toxicity of PBDEs increases with fewer bromines, it is important to understand whether anaerobic microorganisms can debrominate PBDEs. The objectives of our project are to 1) determine whether highly-brominated deca and octa-BDE congeners can be debrominated by anaerobic dehalogenating microorganisms; 2) evaluate the debromination pathway; and 3) quantify the debromination kinetics.

We have mostly completed the first two objectives of this research project. Experiments were conducted with a variety of dehalogenating bacteria on two different highly brominated PBDE mixtures to determine which species are capable of transforming PBDEs. By comparing live samples with autoclaved controls, we found that some of the species were capable of debrominating the octa-BDE mixture down to di-BDE congeners. Several species were capable of carrying out these reactions, including *Dehalococcoides ethenogenes* 195 and three *Desulfitobacterium* species. Only one species, *Sulfurospirillum multivorans*, was able to debrominate deca-BDE to octa-BDE congeners.

Given the complexity of analyzing PBDE congeners with conventional analytical techniques, collaborated with Dr. Peter Korytár at Wageningen IMARES in the Netherlands to use two-dimensional chromatography (GCxGC) to better separate and identify our by-products. When we analyzed the octa-BDE debromination samples using GCxGC, there were many more product congeners than we had previously thought. Among these, we identified several of the most toxic penta and tetra congeners, indicating that the breakdown of less toxic highly-brominated PBDEs can create more toxic products.

Once we had identified bacteria capable of debrominating PBDEs, we exposed three species to seven important PBDEs—five of which are within the octa-BDE mixture, and two of the toxic by-products—to determine the debromination pathway. Using GCxGC techniques, we found that all the PBDE congeners we studied were debrominated to some degree. The debromination pathways were almost identical for all three microbial species tested. Furthermore, we found that certain bromines are preferentially removed. Debromination occurs very slowly for the higher congeners, with only a few parts per billion transformed over the course of three months, while the less brominated tetra and penta congeners can be completely removed by three months. Our results indicate that anaerobic bacteria in the environment might debrominate PBDEs in the same fashion, thereby producing the same by-products.



Our third objective was to determine the kinetic rates of debromination. However, given the extreme hydrophobicity of PBDEs, we experienced difficulty obtaining adequate mass balances and quantifying concentrations with the accuracy required for kinetic calculations. We therefore decided to change our focus to study the aerobic degradation of the less brominated PBDE congeners that are most frequently detected in the environment. We are currently testing bacterial species known to transform PCBs for the ability to degrade PBDEs, notably *Rhodococcus* sp RHA1 and *Burkholderia xenovorans* LB400. Our goal is to understand which congeners are degradeable under aerobic conditions, how quickly this process occurs and what by-products are produced. Since partially oxidized PBDEs are more endocrine disrupting than PBDEs themselves, it is important to understand the exact degradation mechanism.

Publications

He, J., K. Robrock, and L. Alvarez-Cohen. 2006. “Microbial reductive debromination of polybrominated diphenyl ethers (PBDEs)”. *Environmental Science and Technology*, 40 (14): 4429-4434.

Robrock, K., P. Korytár and L. Alvarez-Cohen. 2007. “Pathways for the Anaerobic Microbial Debromination of Polybrominated Diphenyl Ethers”, *Environmental Science and Technology*, in press.

Professional Presentations

Robrock, K. P. Korytár, and L. Alvarez-Cohen. “Anaerobic microbial degradation pathways for seven environmentally relevant PBDE congeners”. American Society for Microbiology General Meeting, Toronto, Canada, May 2007.

Collaborative Efforts

Dr. Peter Korytár at Wageningen IMARES in the Netherlands, Dr. Bill Mohn and Dr. Lindsay Eltis at the University of British Columbia in Vancouver, Canada.

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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 Quantitative PCR assays for host specific and reference targets and apply the assays to identify sources of fecal pollution. Year two of the project has demonstrated significant progress in assay development and the application to watershed samples.

The purpose of this study is to develop Quantitative PCR (QPCR) assays for host specific and reference targets and utilize the assays to identify sources of fecal pollution in the San Pedro Creek Watershed (Pacifica, CA) and focus remediation efforts.

The San Pedro Creek Watershed is an important local recreational resource and steelhead rookery, but has levels of fecal pollution that contribute to coastal pollution and beach closures. Watershed sampling focused on previously untested, potentially polluted sites feeding into the North Fork above the Park Mall culvert (Fig. 1, upper right) and two areas associated with tributaries feeding the main stem from the South, i.e. the vicinity of Adobe Drive at Higgins Way and of Perez Drive (Fig. 1, lower left).

A total of 27 sites were sampled for up to one year, many in wet and dry conditions. Ten sites were sampled on 17 to 21 events, 4 sites on 6 to 9 events, and 13 sites on < 3 events. Enterococcus levels are reported; however, the levels of other fecal indicators (E. coli and total Coliform) paralleled the reported data.

Five sites had extensive fecal pollution, with mean Enterococcus levels >530 CFU/100ml. Twelve sites had mean Enterococcus levels from 90 to 290 CFU/100ml. Nine of the remaining 10 sites had mean Enterococcus levels <35 CFU/100ml. (CA State Standards for coastal water pollution are >35 and >104 Enterococcus CFU/100ml for 30 day geo-mean and single sample, respectively). Of the 5 most polluted sites, two were reference sites, i.e. the North Fork culvert and the Creek mouth. The remaining three sites, all near the intersection of Higgins and Adobe, were the most heavily polluted (mean Enterococcus levels > 948 CFU/100ml) and included surface runoff, a storm drain, and a water filled concrete dissipater. This vicinity was investigated further.

Of the 12 sites with intermediate levels of pollution, two sites were near the Higgins and Adobe intersection, seven were on or near Perez Drive, and the remainder were at or near Frontierland Park and drain toward the North Fork culvert. At each area, there appeared to be several potential sources of fecal pollution.

The heavily polluted Higgins Way concrete dissipater (4' x 3') was found to run perennially even in extended periods of dry weather. Runoff from the dissipater drains down a trail used by dog walkers, children and hikers, through a subdivision, toward San Pedro Creek. Numerous above ground

Figure 1. San Pedro Creek Watershed

water pollution sources potentially feeding into the dissipater were investigated and eliminated. The City of Pacifica drained the dissipater, and cleaned and scoped the underground storm drainpipe found to connect the dissipater to an uphill storm drain. This pipe was in good condition, suggesting that the primary source of fecal contamination for the dissipater arises from storm drain input. Subsequently, the subdivision, onto whose property the dissipater outflow drains, committed to return the outflow from the dissipater to the storm drain system, which would remediate the surface flow of waterborne pollution at this site.

Quantitative PCR (QPCR) assays for the Esp gene of *Enterococcus faecium*, as a specific marker for human fecal pollution, and the 16S rRNA reference gene target diagnostic for total Enterococcus and total fecal pollution were previously developed and validated (see 2006 annual report). DNA from mixed Enterococcus cultures from over 50 watershed samples with elevated Enterococcus levels were analyzed. Twenty eight were local watershed samples, with Enterococcus isolated by the San Mateo County Public Health Laboratory (SMCPHL) and DNA isolated by the PI's laboratory. Although the 16S reference assay reproducibly quantified significant levels of Enterococcus DNA across all standard and watershed samples (C_ts of 12 to 17 for neat samples), the human specific Esp gene target amplified only in standard positive control samples (C68 strain of Esp (C_t 12) plus *E. faecium* and sewage samples from BCS) and not significantly (C_ts > 38) in any of the 28 watershed samples. In contrast, for over 20 watershed and reference samples where Enterococcus and DNA were prepared by BCS of North Florida, the Esp gene target amplified in ca. 50% of the samples (C_ts of 28 to 35) and the reference gene amplified in 100% of samples. It was concluded that the isolation of Enterococcus cultures from IDECC plates by the SMCPHL routinely used for all CA watershed samples artificially skewed the Enterococcus population. Enterococci isolated directly from watershed samples (BCS method) were not subject to this artifact.

At this point, new human specific and reference QPCR assays were developed and compared to the existing assays across numerous positive controls and watershed samples. Based on these preliminary studies, it was concluded that the new human specific and reference assays showed increased sensitivity compared to existing assays. Using the new assays, 2 of 5 watershed samples from Northern California were found to contain significant human fecal pollution, including one sample from the North Fork Culvert of the San Pedro Creek.

In summary, the second year of the project has demonstrated significant progress in assay development and validation, identification of sites in the San Pedro Creek Watershed with highly elevated levels of fecal pollution, and development of strong collaborative ties for remediation efforts.

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* 2006, 67:507-526.

Professional Presentations

Ivanetich, Kathryn, Overview of Northern California Water Quality Research Projects, 18th World Molecular Engineering Network, Cabo San Lucas, May 2007.

Collaborative Efforts

Troy Scott and George Lukasik of Biological Consulting Services of North Florida, and University of Florida, Dept. of Microbiology and Cell Science, Gainesville, FL; Evan Messenger, Biosearch Technologies; Joel E. Baldwin II, Earth Investigations Consultants.

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Fecal Indicator Bacteria and Pathogen Persistence in Dry Beach Sand and Sediment Biofilms

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Our goals over the last year have been to investigate: 1) the influence of environmental factors such as sunlight intensity and temperature on solar inactivation decay constants for FIB in sand, 2) the potential for adverse health impacts due to exposure to sand at an impaired beach, and 3) the extent of sand contamination at two beaches impaired by inland freshwater sources.

In urbanized coastal watersheds, sand can become contaminated with pathogens and fecal indicator bacteria (FIB) from a variety of sources, including sewage spills, overlying water bodies, and contaminated freshwater sources such as storm drains or creeks. Little is known about the persistence and inactivation kinetics of FIB and pathogens in sand. Similarly, the potential for illness through exposure to sand is completely unknown. Our goals over the last year have been to investigate: 1) the influence of environmental factors such as sunlight intensity and temperature on solar inactivation decay constants for FIB in sand, 2) the potential for adverse health impacts due to exposure to sand at an impaired beach, and 3) the extent of sand contamination at two beaches impaired by inland freshwater sources.

Influence of environmental factors on solar inactivation decay constants for FIB in sand

On January 15, 2006, over 2 million gallons of raw sewage were spilled onto the sand at Manhattan Beach, posing a hazard to public health. In collaboration with the Los Angeles County Sanitation District, we set out to investigate solar disinfection of sand as an environmentally-friendly remediation alternative to chlorination, which can result in toxic disinfection by-products. From February 15-21, 2006, sand contaminated by the sewage was spread onto test plots in situ and raked several times a day to determine the effect of raking, as well as solar inactivation, on FIB inactivation rates and Salmonella persistence. Each of the drying beds showed a progressive decrease in both total coliform and E. coli levels throughout the experiment. After eight days of treatment, levels returned to near background, and the incidence of presumptive Salmonella decreased from 92% to 67%.

Bench scale studies were conducted to determine the effect of factors such as solar intensity, moisture, and temperature on inactivation kinetics following two alternative disinfection procedures: solar disinfection with mechanical mixing and iodine application. In both February and June 2007, decay constants measured in controlled experiments using sewage contaminated sand on a rooftop location were very similar to those measured in the field, even though both temperature and intensity of sunlight varied greatly.

Potential for adverse health impacts due to exposure to sand at an impaired beach

From May through September, 2007 and 2008, the Southern California Coastal Water Research Project, in cooperation with Orange County Sanitation District, Heal the Bay, and UC Berkeley, is conducting an epidemiology study of swimming-related adverse health outcomes at Doheny Beach and an impaired beach at Avalon, Catalina (2007) and Malibu Beach (2008). It is a prospective cohort study that will include at least 17,600 swimming and non-swimming beach-goers. Participants will be surveyed for information with respect to gastro-intestinal, respiratory, dermatological, ear, eye, and other non-specific symptoms. Water samples will be tested for FIB, pathogens, and human-specific markers.

Our involvement in this project over the past year resulted in adding two critical components: investigating whether there is 1) a correlation between FIB and pathogen levels in the sediment; and 2) a correlation between health outcomes and FIB or human specific markers in sediment. Questions regarding extent and duration of contact with sand have already been incorporated in the survey. This new sediment component involves analysis of sand samples for E. coli, enterococci, and Salmonella. In addition, we are extracting DNA from sand samples for quantitative PCR analysis of Bacteroides and the esp gene, which are human specific markers.

Extent of sand contamination at two beaches impaired by inland freshwater sources

In 2006, our laboratory measured extremely high levels of FIB near a diverted storm drain under the Santa Monica Pier. The levels decreased exponentially with distance from the source, indicating movement of FIB toward the water. The diversion was renovated during the interval between the summers of 2006 and 2007.

To further explore the effect of a freshwater source on the background levels of FIB at urban beaches, we studied the site of the diverted storm drain under the Santa Monica Pier, and the sand-bermed outlet of the San Juan Creek at Doheny Beach. We took sand samples under the pier from the storm drain outlet down through the swash zone. In addition, we sampled roughly 50 feet north and south of the pier in the dry sand, sand still damp from the previous night's high tide, and sand from the swash zone, as well as corresponding water samples.

Interestingly, enterococci and E. coli levels were higher in 2007 than in 2006, despite the lack of standing water. E. coli levels near the storm drain outlet were 2000 MPN/dry gram in 2006 and almost 394,000 MPN/dry gram in 2007; enterococci levels near the outlet were 217 MPN/dry gram in 2006 and slightly over 16,000 MPN/dry gram in 2007. Again, levels decreased dramatically with distance from the diversion. These results indicate an ongoing issue with this location. Levels on both the north and south side of the pier were low in both years. Similarly, levels in the Doheny pool were very high, but dropped off immediately past the sand saturated with the heavily contaminated freshwater source. This could be due to either the steeper slope of the sand berm than the shoreline slope at Santa Monica, the constant solar exposure during daylight hours (no shading), or a combination of both.

Selected Professional Presentations

Mika, K., C. Lee, R. Moreno, G. Imamura, S. Thompson, V. Conway, G. Fernandez, C.C. Lin, R. Kampalath, J. Jay, Pilot and Bench-Scale Testing of alternative disinfection methods for sewage-contaminated sand, SoCal SETAC Spring meeting, Lake Arrowhead, April 9-10, 2007.

Jay, J.A. Role of environmental biofilms in mercury methylation and persistence of bacteria in beach sand. UC Davis Seminar Series. February 5, 2007; Calltech Seminar Series. January 3, 2007; Washington University, St. Louis, Seminar Series. June 8, 2007.

Collaborative Efforts

We have begun a very meaningful collaboration with Dr. Sharon Walker of UC Riverside. We have received funding from UC Marine Council for a project stemming from our Center for Water Resources Grant. The project involves: 1) addition of a sediment component to a large epidemiology study; 2) fecal source tracking; and 3) a bench-scale investigation of the factors controlling FIB survival and transport in beach sand.

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Optimizing EMA Treatment and qPCR to Determine Viable *E. coli* in Wastewater Effluents

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University of California, Irvine

Public health agencies can take advantage of the rapid and reliable analysis of recreational waters for microbial contamination because this method reduces error in molecular methods by eliminating non-viable sources in the analysis.

Advances in molecular techniques have improved pathogen detection sensitivity and specificity as well as reduced the time to result. However, issues related to cell viability and/or infectivity continue to prevent adoption of DNA Microarrays, Polymerase Chain Reaction (PCR), and Quantitative Polymerase Chain Reaction (qPCR) methodologies by public health, water, and wastewater agencies for routine monitoring. A microarray that simultaneously identifies a number of indicator organisms and pathogens is an ideal solution for public health agencies. Our goal is to develop a simplistic assay that couples ethidium monoazide bromide (EMA) treatment for viability with qPCR to allow accurate quantification of viable target populations which can be comprised of water quality indicator bacteria and/or pathogens. The method can be applied to a wide variety of waters including source water, irrigation and food processing waters, and recreational waters. The problem with many molecular-based identification strategies is the persistence of DNA after cell death, thus bacterial culture techniques remain the accepted standard in determining cell viability by the United States Food and Drug Administration and the Environmental Protection Agency. However, EMA treatment allows amplification of target DNA from culturable and viable cells but prevents PCR amplification of DNA from non-viable or injured sources, thus avoiding the issue of DNA persistence. Our approach can easily be adapted for microarray analyses where real-time monitoring can be achieved. Given current standards, optimization is most cost effective using qPCR methodologies, which would improve pathogen monitoring in environmental waters and potentially increase plant operation efficiencies by rapidly providing information on bacterial populations important in treatment processes.

We adopted a method based on treating samples with EMA prior to DNA extraction in order to prevent PCR amplification of non-viable cells. This approach is based on qPCR using dual labeled probes that allows for the identification and enumeration of genetic markers specific for a target pathogen. Optimization of this assay was performed by evaluating treatments with EMA concentrations of 0, 1, 2, 3, 5, and 7.5 μg/ml on wastewater effluents from primary, secondary activated, and secondary trickling filter treatment processes. Additionally, creek water samples were analyzed to determine the effectiveness in recreational waters. Preliminary data suggested sample turbidity reduced EMA treatment efficiency; therefore we evaluated the turbidity effect on primary effluent diluted to 100NTU and 10NTU.

Results indicate EMA treatment of pure cultures induces a viable but non-culturable state as found by a reduction of over 4 orders of magnitude between the 0μg/ml and 7.5μg/ml EMA concentrations for samples cultured on mTEC media. Although the population of culturable bacteria was reduced, the total population was accurately quantified using qPCR at 7.5μg/ml EMA. In environmental samples, secondary activated effluent responded to treatment with 7.5μg/ml EMA resulting in a 1.5 log reduction compared to the untreated qPCR control and within 0.5 log variation of samples enumerated on mTEC media. However, creek water samples were completely inhibited by this concentration. In both sample types, it is clear that DNA from non-viable, injured, or viable but non-culturable cells were being amplified in the absence of EMA treatment. Primary and secondary trickling filter effluents were resistant to EMA treatments with 0, 1, 2, 3, 5, and 7.5μg/ml EMA as shown in figures 1A and 1B, respectively. Heat-killed primary effluent samples were most resistant to EMA treatment resulting in less than a 0.5 log difference between the 0μg/ml and 7.5μg/ml EMA treated samples (figure 1A). Heat-killed secondary trickling effluent samples produced approximately 1 log difference between the 0μg/ml and 7.5μg/ml EMA treated samples (figure 1B), suggesting higher concentrations of EMA are needed to inhibit qPCR amplification of gene targets from non-viable sources. These results are in agreement with our turbidity analysis. High levels of turbidity reduced the effectiveness of EMA treatment for the quantification of viable bacteria in wastewater effluents. Treating 100NTU and 10NTU samples with less than 7.5μg/ml EMA resulted in quantification of both live and heat-killed bacteria. Inhibition of heat-killed 10NTU primary effluent samples required 7.5μg/ml EMA; 50μg/ml EMA inhibited amplification of live cells in the 10NTU samples however there was no effect on the 100NTU samples.

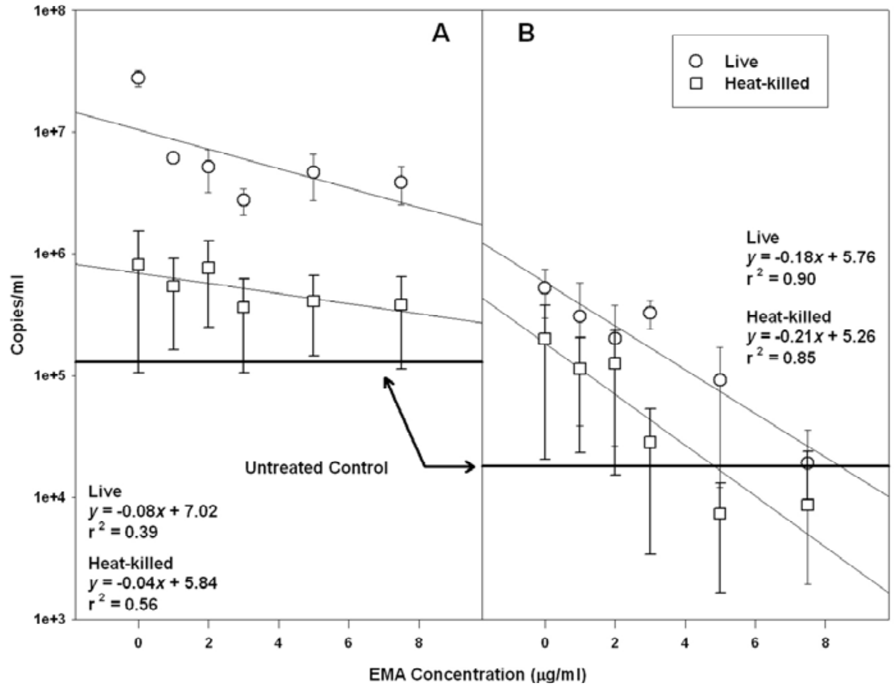

Figure 1A and 1B. EMA qPCR on PCE and STFE.

This research is important to water quality because recreational waters continue to be impacted by high bacterial counts. Public health agencies can take advantage of the rapid and reliable analysis of recreational waters for microbial contamination because this method reduces error in molecular methods by eliminating non-viable sources in the analysis. Wastewater treatment utilities can benefit by optimizing plant operation parameters directly based on actual bacteria populations. Our research provides a simple and efficient method to identify viable pathogens in the environment.

Professional Presentations

Gedalanga, P.B. and B.H. Olson. Optimizing Ethidium Monoazide Bromide Treatment and qPCR to Determine Viable *Escherichia coli* in Wastewater Effluents. 107th American Society for Microbiology General Meeting, May 21-25, 2007, Toronto, ON, CAN.

Gedalanga, P.B. and B.H. Olson. Development of a Quantitative PCR Method to Differentiate Between Viable and Non-Viable Bacteria in Environmental Water Samples. Water Environment Federation Tech. Exhibit Conference, San Diego, CA October 2007.

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

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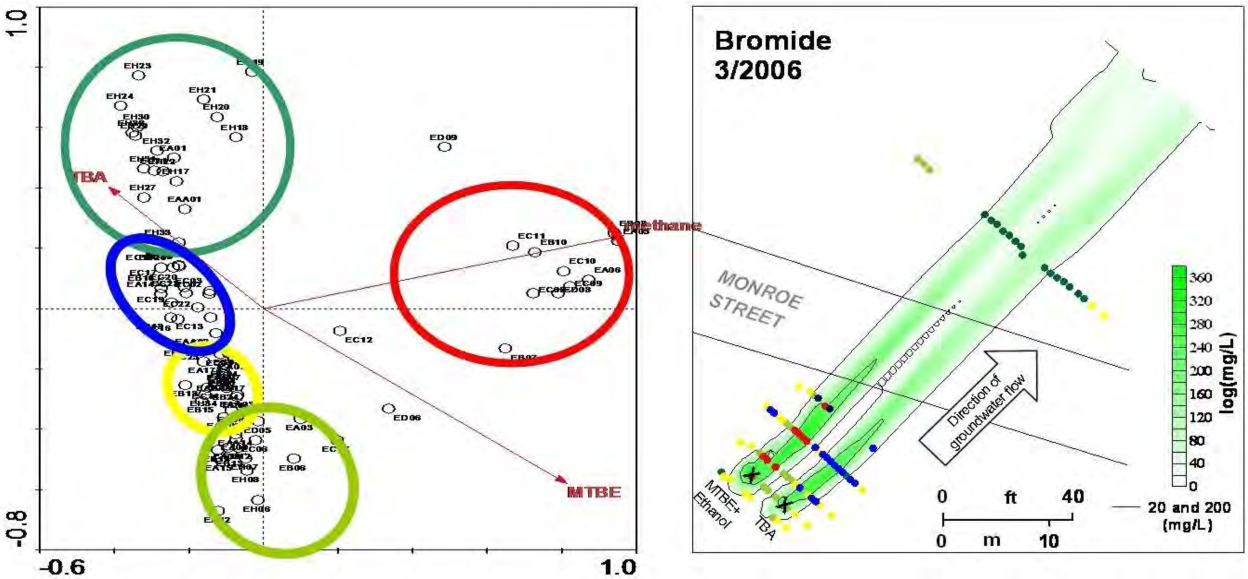
Tertiary butyl alcohol (TBA) is an undesirable byproduct of methyl tertiary butyl ether (MTBE) biodegradation. Ethanol, which is increasingly being used as a gasoline oxygenate, appears to stimulate formation of TBA in groundwater.

Four years after being banned in California, MTBE continues to threaten groundwater resources due to its persistence in the oxygen-deficient subsurface. Introduced into gasoline as an oxygenate and octane enhancer, MTBE enters the environment primarily through leaking underground storage tanks (LUST). Ethanol, the oxygenate replacing MTBE, is expected to interact with existing MTBE plumes via release from LUST. Previous studies have shown that ethanol may reduce biodegradation of other gasoline contaminants. Moreover, ethanol may increase the extent of partial degradation of MTBE to tert-butanol (TBA) which is a more problematic groundwater pollutant than MTBE due to its higher toxicity and mobility. We focus on the role of microbial processes in the conversion of MTBE degradation and TBA production, and how these processes are affected by ethanol.

Our goal is to understand anaerobic MTBE transformation at an environmentally relevant scale, both chemically and at the microbial community level, by means of field experiments and controlled microcosms. Our established research site at the Vandenberg Air Force Base (VAFB) is dedicated to investigating the natural attenuation of gasoline and fuel additives in anaerobic aquifers. In the current study, controlled releases were carried out, consisting of MTBE combined with ethanol and of TBA alone. Anaerobic microcosms of site material were established to 1) demonstrate transformation and degradation, and 2) enrich for and subsequently isolate key microorganisms. Groundwater samples were collected and both bacterial and archaeal populations were enumerated using quantitative polymerase chain reaction (qPCR), and community diversity analyzed using a DNA fingerprinting method, terminal restriction fragment length polymorphism (TRFLP). TRFLP profiles were analyzed using canonical correspondence analysis (CCA), to determine how microbial communities are affected by the contaminants and environmental variables. To aid in data interpretation, a numerical model of the VAFB field site is being assembled, coupling hydrogeological, chemical, and biological data, to investigate the role of biological degradation in MTBE transformation.

Key findings to date stem from molecular analysis of the groundwater samples collected over the region of treatment and from unexposed monitoring wells. Bacterial community structure correlated strongly with MTBE and TBA concentrations, and especially with high levels of ethanol-induced methane. Communities exposed to ethanol + MTBE (red) were distinctly different from those that were exposed to TBA (blue), or unexposed (yellow, light green), whereas there were greater similarities between the TBA and unexposed communities. Impacts were highly localized, with distinct differences apparent between communities across distances of just several feet. However, approximately 120 ft away from the source, bacterial communities became more similar across both treatments, while remaining distinct from background communities (dark green). Based on preliminary



(A) Canonical correspondence analysis of bacterial fingerprints displays groupings of groundwater samples by similarities in composition of their bacterial communities. Axes depicting environmental variables are superimposed over the community distribution plot, allowing a qualitative correlation between clusters and environmental variables (MTBE, TBA and methane concentrations). (B) The clusters determined by CCA are plotted on a map of tracer concentrations (bromide, co-injected with the MTBE + ethanol, and TBA) in the field site. Bacterial community structure appears to be greatly impacted by the release of MTBE (red) and TBA (blue). Areas where methane is generated (red) host very different communities.

comparison with the data on the spatial distribution of bacterial and archaeal population, high concentrations of MTBE and ethanol release elevated population densities of both archaea and bacteria.

TBA is a serious emerging groundwater threat, especially in light of increasing ethanol usage in gasoline reformulations. Little is known about mechanisms involved in transformation of MTBE to TBA in the field and the microbial processes involved. Our results suggest that TBA, MTBE, and ethanol-induced methane concentrations are strong determinants of the indigenous microbial community structure that develops during MTBE transformation. Some changes may persist, potentially altering the degradation of the contaminant in the environment.

The main application of these findings will be for development of economically feasible remediation approaches. Understanding the fate of MTBE plumes under anaerobic conditions and specifically when ethanol is added will allow regulators to establish the optimal guidelines to mitigate the impact of widespread TBA contamination of groundwater resources.

Selected Publication

Mackay DM, N. de Sieyes, M. Einarson, K. Feris, A. Pappas, I. Wood, L. Jacobsen, L. Justice, M. Noske, J. Wilson, C. Adair, KM Scow. Impact of ethanol on the natural attenuation of MTBE in a normally sulfate-reducing aquifer. *Environ. Science & Tech. 2007, 41 (6):2015 -2021.*

Collaborative Efforts

Significant collaborations include modeling work with Prof. Tim Ginn at UC Davis; Jennifer MacKelvie and Prof. Barbara Sherwood-Lollar (Univ. of Toronto) are working on isotope fractionation analysis of MTBE at VAFB; site geochemistry has been characterized with the help of graduate student Nicholas de Sieyes (Stanford); and Prof Kerry Sublette is analyzing TBA in monitoring wells at the site.

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Influence of Bacterial Pathogen Condition on Cell Transport in Groundwater Environments

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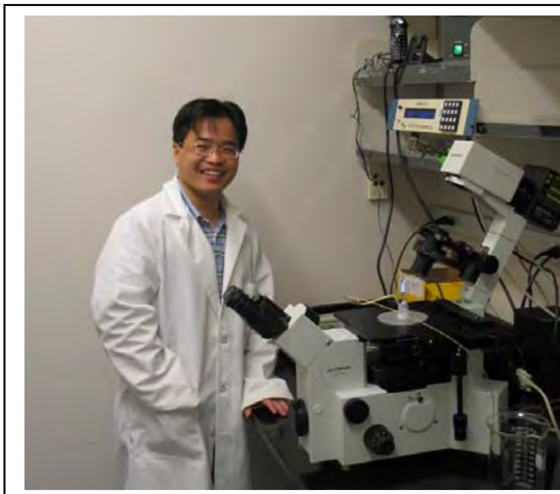
A systematic and extensive examination of the physiological and environmental factors controlling bacterial adhesion and transport is actively being pursued. Currently we are investigating the role that extracellular polymeric substances (EPS) exuded by cells plays in controlling the fate of pathogenic bacteria in groundwater environments.

Due to California's continuing population growth driving demand for an increased municipal water supply and political pressures for decreased reliance on Colorado River water, there is a vital need to ensure protection and quality of groundwater. In the 2,800 square miles covered by the Santa Ana Regional Water Quality Control Board, with a population approaching 6 million people, reclaimed wastewater is increasingly utilized for groundwater recharge. Additionally, non-point source pathogen pollution is a mounting problem due to sources such as dense dairy farming and urban runoff. The ability to predict the fate of human pathogens in the environment is critical, and a mechanistic understanding of bacterial transport in the subsurface environment is imperative for assessing the environmental impact of groundwater contamination from sources including urban runoff, septic tank/ leach field systems, and animal manure from agricultural operations. Such information is also vital for effective design of water quality technologies such as riverbank filtration, wastewater reclamation, and recharge into aquifers.

A systematic and extensive examination of the *physiological and environmental factors* controlling bacterial adhesion and transport in subsurface environments is actively being pursued. Currently we are investigating the role that extracellular polymeric substances (EPS) exuded by bacterial pathogens plays in controlling the adhesive nature of the cells – expressly analyzing the composition of the EPS and adhesion trends in a flowing environment as a coupled phenomenon. This novel approach of investigating the dynamic surface chemistry of bacterial cells and the extent of adhesion will provide a more complete understanding of bacterial pathogen transport mechanisms.

The project is conducted in two core areas. The first is the development of methodologies to extract and analyze the composition of the EPS. These methods were developed in the past; however, the various methods have limitations of efficiency, detection, and reproducibility that need to be worked out and optimized for analyzing EPS of groundwater-borne pathogens. To date, work has involved testing extraction methods involving ethanol, lyophilization (or freeze-drying), and sonication. The compositional analysis involves traditional



Graduate student Gexin Chen with the microscopic RSPF system through which bacterial adhesion can be observed and studied.

spectroscopic quantification techniques; however new methods using HPLC and gas chromatography are currently being explored. The EPS extraction and analysis methods have been tested on a variety of relevant organisms in the lab including *E. coli* (strains including O157:H7, D21g, XL1, and numerous natural isolates), *Salmonella enterica* serovar pullorum *Burkholderia cepacia* G4g, and *Halomonas pacifica* g. The ability to extract and analyze the EPS of *E. coli* isolates from dairy cattle and humans, as well as the *Salmonella* strain, is being tested for cells that have been stressed through starvation (0, 6, 12, and 18 hours). Additionally, an ongoing study is looking into the influence of solution chemistry (artificial groundwater at varying ionic strengths) and exposure time on *Salmonella* EPS production.

The second area of research involves the investigation of cell adhesion and transport in groundwater environments. This work is conducted in two experimental systems: 1) a packed bed column, and 2) a radial stagnation point flow (RSPF) cell. Both systems simulate transport of bacteria within porous media. The packed bed column is a macroscopic approach of quantifying cell transport; whereas, the RSPF system is a microscopic method of observing cell adhesion to a surface. Experiments in both systems are conducted under solution chemistry and hydrodynamic conditions simulating the subsurface environment. Experiments in the packed bed have been conducted utilizing *E. coli* (strains including O157:H7, D21g, XL1, and numerous natural isolates) and *Salmonella enterica* serovar pullorum. *Burkholderia cepacia* G4g and *Halomonas pacifica* g have been used in the RSPF system. To fully analyze the trends in cell transport, the surface chemistry of the bacterium requires consideration. The EPS composition and content provides considerable insight into this surface chemistry. Hence, EPS analysis has been compared to the transport data. The trend observed, regardless of cell type or environmental condition, is that the charge on the cell surface and the ratio of sugars to proteins within the EPS provides an indication of the type of interaction forces that will result between the cells and the surfaces. Ongoing work will provide further insight into the applicability of this trend and whether this may provide a future predictive tool.

The overall goal for this project is that this fundamental research will provide a greater understanding of how environmental conditions influence cell fate in groundwater environments; and hence, lead to more effective water management and re-use practices in the future.

Publications

Chen, G. and Walker, S.L., The role of solution chemistry and ion valence on the adhesion kinetics of groundwater and marine bacteria. *Langmuir*, 2007, 23 (13) 7162-7169.

Selected Professional Presentations

Kim, H.J. and S. L. Walker, *Escherichia coli* Deposition and Transport in Porous Media: The coupled role of temperature and solution chemistry, American Chemical Society 81st Colloid & Surface Science Symposium, Newark, DE, June 2007.

Walker, S.L, Mechanisms of Bacterial Adhesion and Transport in Aquatic Systems, University of Sheffield, Sheffield, England, April 2007; University of California, Davis, CA, February 2007; and University of California, Berkeley, CA, October 2006.

Walker, S.L, What's in Your Water? UCR Life Program at the UCR Extension, Riverside, CA, February 2007.

Kim, H., S. ShojaeTazehkand , and S. L. Walker, *E. coli* deposition and transport in porous media: Influence of solution chemistry and bacterial surface polymers, American Institute of Chemical Engineers National Meeting, San Francisco, CA, November 2006.

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Modeling Non-point Source Contributions of Host-specific Fecal Contamination in San Pablo Bay

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The project focuses on coupling microbial source tracking, pathogen analysis, and validated ultrafiltration technology with a solid 3-D modeling approach for a case study of San Pablo Bay. A major outcome of the research project is to provide a tool for decision makers to maximize financial resources.

This project focuses on coupling microbial source tracking, pathogen analysis, and validated ultrafiltration technology with a solid 3-D modeling approach for a case study of San Pablo Bay. A major outcome of the project is to provide a tool for decision makers to maximize financial resources. End users may include water control boards, wastewater treatment facilities, managers of recreational lands and natural resources, and others involved in water quality monitoring.

The four objectives of the project are:

Objective 1: Develop sea bird (especially seagull) – specific molecular PCR assays to quantify their contribution to bacterial fecal loads in San Pablo Bay and its tributaries.

Objective 2: Monitor 5 locations in the 3 tributaries for *Bacteroidales* and a suite of pathogens during 4 events reflecting both dry and wet weather conditions.

Objective 3: Demonstrate the utility of a combination of theoretical/numerical modeling and innovative molecular PCR assays to determine experimentally, and then forecast, the extent of fecal contamination of a water body, and for the identification of the sources of that contamination.

Objective 4: Initiate development of quantitative tools that could help stakeholders in making decisions to minimize public health risks in San Pablo Bay, e.g., best management practices aimed at reducing source-specific contamination determined by *Bacteroidales*-based assays.

During the first phase of this project, we have made progress for each objective:

Objective 1: Our published method for quantitative universal *Bacteroidales* PCR (qPCR), the assay BacUni-UCD, did amplify *Bacteroidales* in mixed seagull feces, although fewer gene copies were determined relative to feces from other warm-blooded animals. Therefore, non-*Bacteroidales* 16S rRNA target sequences will need to be identified for development of a seagull-specific qPCR assay.

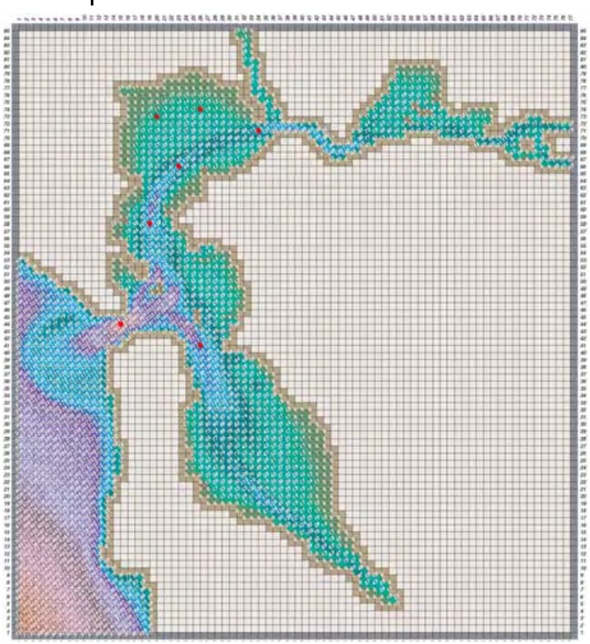
Objective 2: Locations for water sampling were selected to best represent the fecal contamination contributed to San Pablo Bay from fresh water sources. Sample sites include the Napa River, Sonoma Creek, the Petaluma River, the Napa Sonoma Marsh, Suisun Bay, Gallinas Creek near China Camp State Park, and inside the Bay. The first field measurement and sampling event is planned in October 2007. Exploratory numerical tests with Si3D are helping to determine the best sampling locations in San Pablo Bay. Moreover, preliminary experiments were performed to determine decay rates of host-specific *Bacteroidales* cells and their DNA in the environment. Stool samples of cows, dogs, and humans were used. The decay rates will be used in the mathematical/numerical models being developed.

Objective 3: One- and two-dimensional (1-D and 2-D) mathematical/numerical models of the fate and transport of *Bacteroidales* in water bodies were developed. The models have been validated via comparison with analytical solutions and via assessing the correctness of the model solution under diverse scenarios of interest. These 1- and 2-D numerical solutions will become crucial in obtaining dispersion coefficients and decay rates from observations in different rivers and estuaries.

The first analyses with the Si3D code were performed for all of San Francisco Bay, and preliminary results, including the ADR transport equation for *Bacteroidales* in Si3D, were obtained. An assessment of the impact of grid resolution into the numerical result in terms of flow and transport of *Bacteroidales* is underway. Grid sizes of 200 to 1,000 meters are being tested.

Moreover, a comprehensive list of Internet resources was compiled for water quality, flow, and weather data in the San Francisco Bay and Estuary. These data are crucial for a sound modeling of San Pablo Bay.

Objective 4: Modeling of *Bacteroidales* concentration within the San Pablo Bay will be accomplished after a set of localized concentrations of *Bacteroidales* has been obtained. Preliminary runs are currently underway to optimize placement of sampling locations.



Grid spacing and bathymetric data for the computational domain of the San Francisco Bay and Estuary, indicating the seven locations in which velocity profiles obtained from the numerical solution are shown. (This run corresponds to a grid size of 1,000 m.)

Selected Publications

Santo Domingo, J.W., D.G. Bambic, T.A. Edge and S. Wuertz, Quo Vadis Source Tracking? Towards a Strategic Framework for Environmental Monitoring of Fecal Pollution, *Water Research,* 2007*,* 41: 3539-3552.

Kildare, B.J., C.M. Leutenegger, B.S. McSwain, D.G. Bambic, V.B. Rajal and S. Wuertz, 16S rRNA-based Assays for Quantitative Detection of Universal, Human-, Cow- and Dog-Specific Fecal *Bacteroidales:* A Bayesian Approach, *Water Research,* 2007, 41:3701-3715.

Rajal, V.B., B.S. McSwain, D.E. Thompson, C.M. Leutenegger, B. Kildare, and S. Wuertz, Validation of Hollow Fiber Ultrafiltration and Real Time PCR Using Bacteriophage PP7 as Surrogate for the Quantification of Viruses from Water Samples, *Water Research,* 2007, 41:1411-1422.

Collaborative Efforts

Dr. Drew M. Talley and Ms. Marina Psaros at Romberg Tiburon Center, San Francisco National Environmental Research Reserve (NERR) have provided assistance with site selection for field measurements and public outreach, e.g., workshop planning and maintenance of a project website, respectively.

End users are providing input on the research as it progresses.

Additional funding from the Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET) has allowed us to expand the project beyond the scope of the original UC Water Resources Center grant.

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NDMA Formation during Chlorination and Chloramination of Aqueous Diuron Solutions

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The phenylurea herbicide diuron is widely used and frequently detected in California source waters, and has a structure suggesting that it might be a precursor of N-nitrosodimethylamine (NDMA). This study sought to quantify the potential of NDMA formation from diuron solutions under varied chlorination or chloramination conditions. Significant quantities of NDMA were produced during dichloramination of diuron under reactant concentrations representative of water treatment operations, suggesting a need for further investigation to accurately assess the human risk posed by diuron with respect to NDMA formation potential.

Formation of the extremely potent carcinogen N-nitrosodimethylamine (NDMA) during chloramine disinfection from waters containing secondary amines is well documented. Dimethylamine (DMA) has served as the model NDMA precursor in most studies; however NDMA formation typically cannot be fully accounted for by the known formation mechanisms and the amount of DMA present, indicating the other precursors are present in drinking waters. The phenylurea herbicide diuron is one of the most widely used herbicides in California, has been frequently detected in California's water supplies, and has a structure including a tertiary amine functionality that suggests it might be an NDMA precursor. This project was intended to quantify the potential of NDMA formation from aqueous diuron solutions under varied conditions of chlorine or chloramine disinfection.

In this study, NDMA formation was consistently observed in aqueous diuron solutions during chloramination and even chlorination in the absence of the added ammonia, which has been usually the source of the nitroso-nitrogen in NDMA during chloramination of other secondary amines. It appears that both nitrogen atoms in NDMA can be provided solely by diuron itself during chlorination in the absence of ammonia. In the experiment of diuron chlorination, diuron was rapidly oxidized and the trend of NDMA formation was consistent with that of free chlorine depletion over the time scale of the experiment (Figure 1). A lower yield of NDMA was observed when a lower concentration of diuron was applied (Figure 2), and a pH dependence of NDMA formation in aqueous diuron solutions between pH 6 and 10 was observed consistent with previous NDMA formation studies using DMA as the model precursor. At low pH (pH 4) a much higher yield of NDMA was detected, which may be attributable to the greater availability of DMA due to the enhanced hydrolysis of diuron that can be catalyzed at low or high pH.

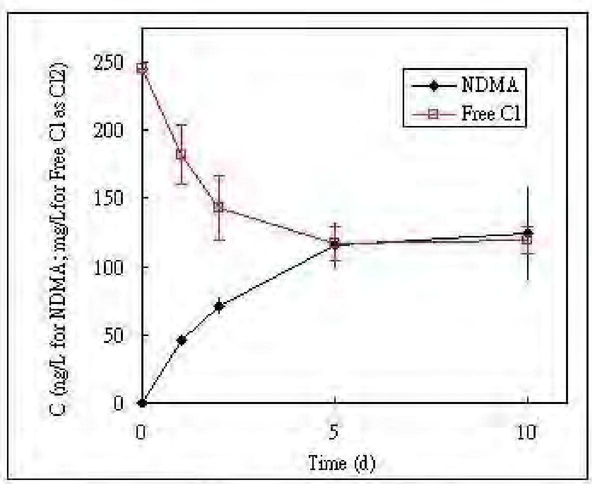

Figure 1. NDMA and free chlorine residual concentrations during the reaction between diuron and NaOCl at pH = 8 ± 0.2. The initial concentrations of diuron and free chlorine were 20 mg/L and 245 mg/L as Cl_2, respectively. The point and error bar depict the mean value and one standard deviation, respectively.

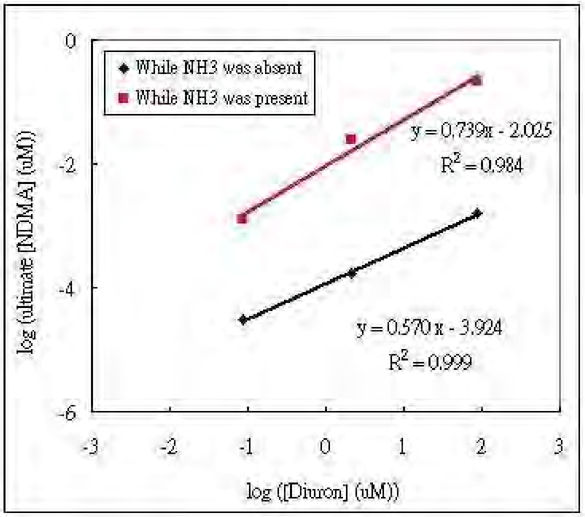

Figure 2. NDMA formation under different initial diuron concentrations at pH = 8 ± 0.2 after 5 days contact time while NH_3 was either present or absent in the system. The initial concentration of NaOCl in each experiment was 245 mg/L as Cl_2. The value and bar depict the mean value and one standard deviation, respectively.

The addition of ammonia during diuron chlorination significantly enhances NDMA formation (Figure 2). For a given chlorine and diuron dose, NDMA formation increased in the order of $OCl^- < NH_2Cl < NHCl_2$, a result consistent with previous NDMA formation studies indicating $NHCl_2$ is a more potent NDMA-forming oxidant. Significant quantities of NDMA, more than two orders of magnitude above the EPA clean-up level (0.7 ng/L), were produced during dichloramination of diuron using a low dichloramine concentration and a diuron concentration at the upper end of typically detected concentrations in California (20 μg/L), suggesting a need for further investigation to accurately assess the human health risks posed by diuron with respect to NDMA formation potential.

Dichloramine is not intentionally used for disinfection, but it will be present to some extent in systems using chloramination. Two primary fragment molecules, DMA and dichloroaniline (DCA) may be released from diuron and play important roles in NDMA formation during chlorine or chloramine disinfection. Although the risk identified here is likely small in comparison with the whole spectrum of risks associated with disinfection, avoiding this particular risk involves avoiding chloramines (e.g., nitrification prior to free chlorine application for wastewater, or breakpoint chlorination for source waters containing NH_3); or if chloramination is desired, the addition of free chlorine prior to NH_3, the avoidance of low pH and the control of Cl to N ratio. It is also important to distinguish the difference between diuron concentrations in source waters and those in the disinfection process. To correctly determine the risks posed by diuron in terms of NDMA formation to downstream water users, the potential removal of diuron during water treatment operations must be taken into account. Further studies are needed to better define the pathway and kinetics of NDMA formation during diuron chlorination and chloramination to support the accurate assessment of human health risks posed by diuron in water sources. Understanding the NDMA formation pathway will also support the broader goal of developing effective strategies for minimizing NDMA formation during disinfection operations.

Publications

Chen, W-H and T.M. Young, NDMA Formation during Chlorination and Chloramination of Aqueous Diuron Solutions, *Environmental Science and Technology*, in press.

Professional Presentations

Wei-Hsiang Chen and Thomas M. Young, Potential Transformation By-Product and Associated Risk of Diuron in Disinfection Process, Occurrence, Formation, Health Effects and Control of Disinfection By-Products in Drinking Water, The Division of Environmental Chemistry, American Chemical Society, Chicago, IL, March 2007.

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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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University of California, Riverside

Imperial Valley agriculture confronts reductions in water supply due to its adherence to the interstate agreements regarding Colorado River water allocation and a recent agreement with the San Diego County Water Authority contained within the Quantification Settlement Agreement. Our results show that the economic impact on grower income and regional economic well-being can vary substantially depending on how the growers are regulated and if they are allowed flexibility in how they participate in a water market.

This study investigates the effects of increased water scarcity in Imperial County, California related to two recent changes that limit the amount of water available to agriculture. California no longer enjoys the surplus Colorado River water from Arizona and Nevada which in the past has exceeded 800,000 acre feet per year. Additionally, a historic water transfer agreement between the San Diego County Water Authority (SDCWA) and the Imperial Irrigation District (IID) was approved requiring a total of 150,000 acre feet to be transferred annually to the SDCWA by 2017 and as much as an additional 200,000 acre feet of water to be transferred annually thereafter. We investigate the effects of these reductions on agricultural production, water use, land use, potential drainage flows to the Salton Sea, and employment within Imperial County. It should be noted that Imperial County has extremely high rates of unemployment, and the agriculture sector is the 2nd largest employer in the local economy and the largest water user.

The analysis uses three programming tools to develop a model that links plant growth, net returns from agricultural production, and employment. A plant growth model is developed which models the relationship between water use, yield, and drainage; a programming model is used to calculate net returns to land and management in the agricultural sector for five crops considered to be representative of the crops grown in the Imperial Valley; lastly, a link between the agricultural sector and the broader economy is analyzed to estimate the impacts on employment. These models are used to evaluate three different policy options, including the current water regulations where growers are constrained in how they free up water to transfer to the SDCWA (policy 1); water regulations that would allow growers flexibility in meeting the water transfer allowance to SDCWA (policy 2); and finally, water regulations that would allow growers flexibility in both the manner in which they free up water and in the amount they choose to free up (policy 3).

Our results suggest that under the current rigid water regulations (policy 1), the agricultural sector loses between $27 (policy 2) to $34 million (policy 3) annually relative to if growers were allowed more flexibility in terms of how they can free up water to sell and the amount of water they can free up to sell to the SDCWA. Unfortunately, under the more profitable regulations, growers sell substantially more water than under the current system; consequently, there would likely be a noticeable reduction in drainage water reaching the Salton Sea barring some mitigation activities.

From a regional economic perspective, the impacts on the local economy, both in terms of income and employment, is highly dependent upon whether the income from the sale of the water stays within the region. If so, the income (employment) impacts of any of these regulations varies from an annual loss of $26 million (337 jobs) to a gain (loss) of $12 million (41 jobs). Alternatively, if the income from the sale of the water goes to agents outside the local economy, the income (employment) impacts of any of these regulations varies from an annual loss of $43 million (465 jobs) to a loss of $45 million (485 jobs). Given that the actual amount of income staying within the local economy will be somewhere between these two extremes, the actual income and employment effects will be bounded by the above estimates.

In conclusion, allowing growers more flexibility in how they can participate in a water market can have strong positive impacts on agricultural and regional income and employment; there may be some adverse impacts on the quantity of drainage water generated that could negatively impact the quantity and quality of inflow water to the Salton Sea.

Publications

Schwabe, K., P. Schuhmann, K. Baerenklau, and N. Nergis, Fundamentals of Estimating the Net Benefits of Ecosystem Preservation: The Case of the Salton Sea, *Hydrobiologia*, accepted 7/1/2007.

Knapp, K.C. and K.A. Schwabe. Spatial Dynamics of Water and Nitrogen Management in Irrigated Agriculture. *American Journal of Agricultural Economics.* Accepted 8/10/2007.

Professional Presentations

K. Schwabe and N. Nergis. Fundamentals of Estimating the Net Benefits of Ecosystem Preservation: The Case of the Salton Sea. Salton Sea Centennial Symposium: A Salton Sea for the 21st Century: Science, Rehabilitation, and Management. San Diego, CA, April 1, 2005.

Collaborative Efforts

This project included significant interaction with other economists (K. Knapp and K. Baerenklau, UC Riverside), and an extension agent at the UC Davis Imperial County Desert Research Center (Dr. K. Bali). Retired Extension Agent Dr. K. Mayberry's research also contributed greatly to this research.

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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 policies for managing California's limited water resources are also encouraged in this category.

The Politics and Practice of Watershed Restoration: Insights from the Russian River Watershed, Northern California

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Watersheds are ecologically and socially dynamic and restoration efforts that fail to recognize the importance of the social context will fail to address the sources of degradation.

Over the last two decades California has allocated billions of dollars to watershed restoration activities through legislation and voter-approved bonds. Yet, the implications of restoration remain ambiguous since there has been little examination of restoration accomplishments and almost no analysis of the political context of restoration. This research addresses these gaps, utilizing a case study of the Russian River in Northern California.

We identify trends that shed light on both the ecological and political implications of restoration at a basin scale by examining a database of 787 restoration projects implemented in the Russian River basin since the early 1980s. Although over $47 million has been spent on restoration in the basin, dominant forms of restoration are limited in scope to small scale projects that focus on technical solutions to site-specific problems.

Sixty-two percent of all restoration projects are devoted to road repair, riparian stabilization, and in-stream structures. These types of projects do not address the broader social drivers of watershed change such as land and water uses. We suggest that restoration can become more effective by addressing the entire watershed as a combination of social and ecological forces that interact to produce watershed conditions.

Conservation and restoration are as much about social processes as physical ones, however social factors are not subjected to the same analysis as technical ones under prevailing analytical frameworks. We argue that watersheds are ecologically and socially dynamic; and that restoration that does not recognize the social context will fail to address the sources of degradation.

To explore these larger issues, we examine a case study of the Russian River watershed, asking**:** *How do social relations influence the practice of watershed restoration?* This research provides an analysis of the institutional framework of restoration, addressing several sub-questions including:

- What are the landscape-scale and site-specific characteristics of watershed restoration activities (types of work done, total cost, organizations involved, measures of success)?
- How do shifts in federal and state policies regarding water resources influence the practice of watershed restoration?
- What policy interventions are likely to address sources of watershed degradation?
- What are the linkages between this case study and current patterns of watershed restoration throughout California?

The Russian River watershed is an ideal location due to the concentration of restoration activities and on-going studies conducted by the University of California Cooperative Extension offices in the area. After decades of conflict between competing resource users, the river's once meandering path has been forced into a narrow channel for flood control and farming; native steelhead and salmon species have been listed as endangered; and the river has the dubious distinction of being named one of the twenty most threatened rivers in the United States by American Rivers two years in a row (1996 and '97).

Our research examines where restoration happens, how it happens, and who benefits. In examining where restoration happens, the results show that restoration projects are over-represented on timberland, rural residential land, and vineyards. This indicates that restoration dollars disproportionately benefit segments of the population involved in resource extractive and intensive activities like timber production and agriculture. In examining how restoration happens, our research reveals distinct preferences in the types of projects funded by three major funding institutions in the basin, demonstrating the dominance of site-specific in-stream, riparian, and road related improvements. Therefore other objectives in publicly funded restoration programs, such as water quality and quantity, and education, are not widely addressed by current restoration practices.

Modified hydrologic conditions, in addition to habitat alteration, can greatly impact anadromous salmon runs (Moyle 2002). Current land and water uses in the basin have greatly modified hydrologic conditions. Large dams for urban use and the cumulative effect of small-scale water projects for agriculture and rural development have altered natural flow regimes. Fish recovery will require changes in water management including more natural flow regimes for dam releases and increased winter storage in the upper part of the watershed where vineyards are currently relying on surface and subsurface stream flows in the dry season.

Improving the efficient use of water in the Russian River requires participation and coordination among agriculture and urban users to identify future alterations that could increase efficiencies. Water rights are also under investigation and it will be necessary to provide incentives to generate alternatives to the use of historic rights that when exercised can result in impacts to stream habitat critical for salmon recovery. With increased recognition of the cumulative effects of groundwater use in California, increased regulation has been proposed and while this may be necessary in some cases, integrated solutions developed by coordinated stakeholder decision making processes may be more sustainable in the long run. Also, rural residential expansion has resulted in an increase in the number of domestic wells that can draw down upland stream flow levels upon which juvenile salmon rely for over-summer survival and can result in increased sediment levels in downstream spawning gravels (Lohse et al., submitted). Therefore reducing sprawl into wildlands would both reduce the demand on water and protect remnant upland habitat. Part of the solution to sprawl is to increase urban densities, which will need to be accompanied by water conservation.

Changes in policy and management to foster restoration need to be managed adaptively; monitoring the coupled human and natural system is an essential part of restoration. Our research clearly shows how little we currently invest in monitoring restoration outcomes which in the end will prevent us from improving our restoration outcomes. It is our intent to evidence, rather than explain, how and why restoration is not only an ecological activity, but also an inherently social one. Only through understanding and analyzing natural resource management in an integrated manner can sustainable solutions be found.

Publications

Langridge, R., J. Christian-Smith, and K. A. Lohse. 2006. "Access and Resilience: Analyzing the Construction of Social Resilience to the Stress of Water Scarcity." *Ecology and Society* 11 (2): 18. Online at: www.ecologyandsociety.org/vol11/iss2/art18/

Christian-Smith, J. (Dissertation) 2006. The Politics and Practice of Watershed Restoration: Insights from the Russian River Watershed, Northern California. UC Berkeley.

Collaborative Efforts

Our lab has a collaborative relationship with researchers at the Hopland Research and Extension Center, which houses a GIS lab with extensive spatial data analysis resources.

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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 and elsewhere in California. Topics include policy analysis and systems optimization of sustainable salinity and drainage management options for the western San Joaquin Valley; fate and impacts of various trace element chemical species in the environment; 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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The project focuses on evaluating the integration of accelerated chemical demineralization (ACD) for scale mitigation with membrane reverse osmosis (RO) desalting to enable high RO recovery. The technical and economic feasibility of the integrated ACD/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 Valley (SJV) ranges from about 2000 to nearly 29,000 mg/L total dissolved solids (TDS). In recent years, membrane desalination has been proposed as a practical technology to reduce the salinity of this brackish groundwater. Membrane desalination for SJV brackish water would have to be carried out at relatively high water recovery in order to limit the volume of reverse osmosis (RO) concentrate. However, at high water recoveries the concentration of mineral salt ions in the RO feed channel may increase to levels above the solubility limits of various sparingly water soluble mineral salts (e.g., calcium sulfate, calcium carbonate and barium sulfate). These salts crystallize directly on the membrane surface and may also precipitate in the bulk and subsequently deposit onto the membrane surface. Resulting mineral scale build-up on the membrane leads to permeate flux decline, shortened membrane life, and increased operational cost. High recovery RO desalting is feasible if mineral salt scaling, which limits recovery, can be alleviated.

This project focuses on evaluating an approach to high recovery desalting of brackish water that makes use of an interstage accelerated chemical demineralization (ACD) of the RO concentrate stream, in order to enable secondary RO desalting to further increase the overall product water recovery. In the first phase of the project, a systematic theoretical thermodynamic solubility analysis was carried out for selected source water locations in the SJV to evaluate the limits on product water recovery imposed by mineral salt scaling. The analysis revealed that, even with the use of antiscalants and acidic pH adjustment, primary RO recovery would range from about 58%-80%. Laboratory membrane scaling studies were then carried out for selected field brackish water samples from representative locations in the SJV to evaluate the scaling propensity of these source waters. These studies have shown that, for primary RO desalting of SJV brackish water (typically high in gypsum saturation), the carbonate ion suppresses gypsum crystallization while the sulfate ion suppresses calcium carbonate scaling. Therefore, RO operation can be carried out at a higher pH than would be predicted by thermodynamic solubility analysis. The addition of antiscalants can assist in enabling reasonable recovery in the primary RO step. The addition of coagulants to aid in feed pretreatment must be carefully evaluated as the present study revealed that filtration aids could severely reduce antiscalant effectiveness. Direct real-time RO membrane surface imaging was utilized to evaluate and compare antiscalant effectiveness. Such an approach can be used to rank antiscalant effectiveness, optimize dosage, compare candidate membranes based on scaling propensity, and optimize operating conditions.

Recovery up to about 95% was shown feasible, via secondary RO desalting of the chemically demineralized primary RO concentrate, based on lab experiments and a limited pilot plant study. Accelerated chemical precipitation, at high pH with calcium carbonate seeding, was found to be an

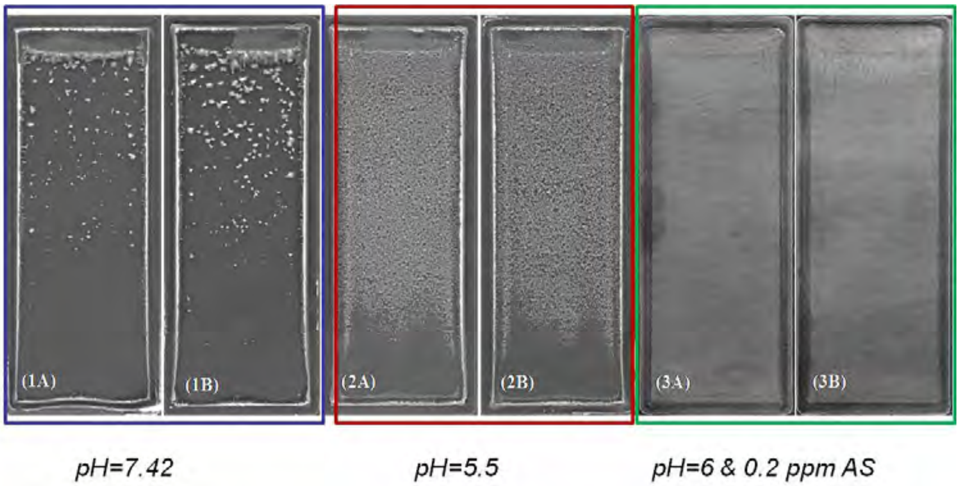

Figure 1. Images of gypsum scale formed on RO membrane from a scaling test with a dual membrane cell for a water source location in the SJV. Scaling is lower at pH 7.42 (the native pH of the water source) relative to pH of 5.5, due to the suppression of gypsum scale by the carbonate ion and suppression of carbonate scale by the sulfate ion. (Gypsum saturation index= 2.5)

effective demineralization method for primary RO concentrate rich in carbonate. However, chemical demineralization at high pH with gypsum seeding was more appropriate for desupersaturation of primary RO concentrate high in gypsum saturation, but with a low calcium carbonate precipitation potential. For this latter type of water source, recycling of the concentrate from the secondary recovery RO stage may be necessary in order to reach the target recovery level of >90%.

To evaluate the various process configuration options and optimal operating conditions for high recovery desalting, a process design methodology was developed for the integrated primary RO-ACD-secondary RO process. Laboratory studies confirmed that the precipitation kinetics was reasonably fast for practical implementation of the RO-ACD-RO desalting process. Current efforts are focused on evaluating the impact of antiscalant type and dose on the crystallization kinetics, with respect to the pH and size distribution of crystal seeds in the interstage crystallizer.

Selected Publications

Rahardianto, A., J. Gao, C. J. Gabelich, M. D. Williams and Y. Cohen. “High recovery membrane desalting of low-salinity brackish water: Integration of accelerated precipitation softening with membrane RO,” *J. Membrane Science*, 2007 289 123–137.

Gabelich, C. J., M. D. Williams, A. Rahardianto, J. C. Franklin and Y. Cohen. “High-recovery reverse osmosis desalination using intermediate chemical demineralization,” *J. Membrane Science*, 2007 301 131-141.

Selected Professional Presentation

Cohen, Y., "High recovery membrane RO desalination of brackish water: Opportunities and limitations", 233rd ACS National Spring Meeting. Mar. 27, 2007, Chicago, IL.

Collaborative Efforts

The California Department of Water Resources, Salinity Drainage Program provided in-kind contributions of water samples from various locations in the SJV and water quality analysis of those samples.

The Metropolitan Water District of Southern California provided antiscalant samples used in the study. A membrane concentrator used to evaluate high recovery RO desalination was provided as an in-kind contribution.

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 contributions for use in this study.

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Bioaccumulation and Biotransformations of Organic Material-Borne Selenium in Mosquitofish

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Correct determination of dimethylselenoxide by an HPLC-HG-AAS will be helpful to study the mechanisms of Se toxicity in fish and waterfowl.

Formation of superoxides and oxides such as dimethylselenoxide (DMSeO) from oxidative reactions of methanselenol (CH_3SeH) and dimethylselenide [$(CH_3)_2Se$] is one of the important mechanisms causing Se toxicity in fish and waterfowl. Because of a lack of analytical methods for directly measuring the superoxides and oxides, the mechanisms responsible for causing deformity of fish and waterfowl have not been studied in detail. In this study, a high performance liquid chromatography and hydride generation atomic absorption spectrometry (HPLC-HG-AAS) system has been used to directly measure DMSeO in solution. An HPLC was used to separate DMSeO with other HG-active Se compounds such as selenomethionine (Semet) and selenite [Se(IV)], and an optimum concentration of $NaHB_4$ and HCl was used in the HG system to maximally increase the DMSeO signal and decrease interferences from other HG-active Se species, and AAS was used to determine it. A detection limit of DMSeO was <5 µg/L. Recovery of spiked DMSeO in drainage water was close to 100%. This new method will be helpful to study the mechanisms of Se toxicity in fish and waterfowl.

Publications

Zhang, Yiqiang, and William Frankenberger, Jr., 2007. Supplementing *Bacillus* sp. RS1 with *Dechloromonas* sp. HZ for enhancing selenate reduction in agricultural drainage watet. *The Sciences of Total Environment*, 2007, 372: 397-405.

Zhang, Yiqiang, Ben. C. Okeke, and William Frankenberger, Jr., Bacterial Reduction of Selenate to Elemental Selenium Utilizing Molasses as a Carbon Source. *Bioresources Technology*, 2007, (in press).

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

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Development of an ecological monitoring program to quantify potential long-term impacts of real-time wetland salinity management on habitat and health of the biological resource.

This project is aimed at developing and testing a pilot-scale real-time water quality management program 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 from the Delta to private duck clubs, as well as State and Federal Refuges. Returning drainage from the wetlands contains elevated salts, carbon and nutrient loads 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 selected from State and privately managed wetlands in the Grassland Water District. For each pair we are comparing traditional management practices with a delayed seasonal drawdown 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 real-time sensors measuring electrical conductivity, temperature, and stage have been constructed and are currently in operation 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 for a second year. Through the development of techniques to differentiate specific spectral signatures, 29 wetland plant associations have been recognized. Over 500 ground truth locations were sampled to verify the accuracy of these techniques. Of the 29 signatures, 9 were moist-soil plant associations that included _Crysis schoenoides_

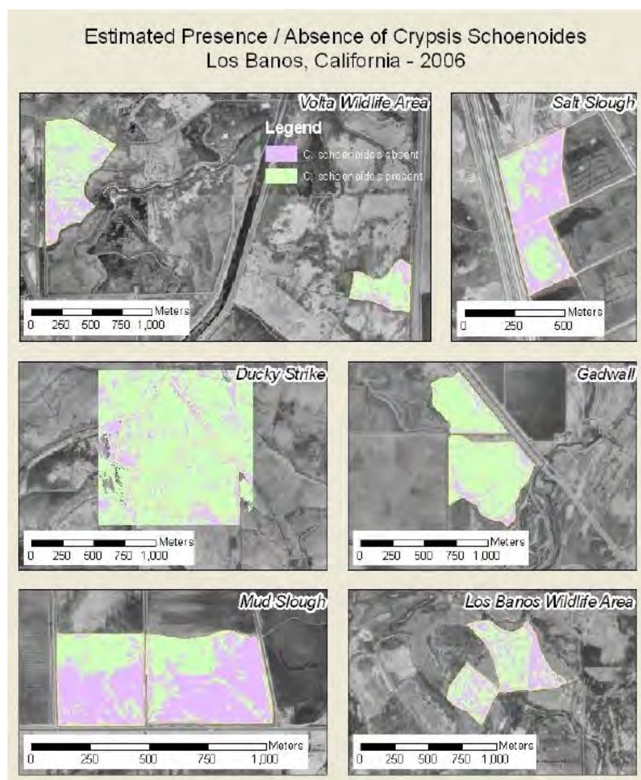

Figure 1. _Crypsis schoenoides_ (swamp timothy) maps for the 6 paired wetland sites. Maps were developed using spectral signatures for 29 moist-soil plants found within the Grasslands Ecological Area.

(swamp timothy), the dominant moist-soil plant managed for in the Grasslands Ecological Area. With the spectral signatures, classification was performed to estimate areas of swamp timothy presence and absence across the entire study area (Figure 1).

- High resolution soil salinity maps were created using an elongated electro-magnet (EM-38). Transects 15 meters apart were walked, logging measurements at 2 second intervals. The EM-38 produces a relative soil salinity map that must then be calibrated to salinity values measured from physical samples. A total of 12 soil samples per field were used to calibrate the maps. While these results are currently being analyzed, correlations between the electromagnet values and the physical samples are expected to be linear (as in past studies). Patterns shown by the uncorrected relative salinity maps can be used to show the general salt distribution within each field.
- A prototype system of stationary sensor arrays observation of wetland pond salinity was tested near the end of the spring 2007 drawdown (Figure 2). The stationary arrays will enable continuous monitoring of moist soil conditions in the wetlands. Soil parameters to be measured include temperature, electric conductivity, and soil moisture. Multiple sensor arrays will be installed to capture data during the Spring 2008 drawdown period.
- 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, enabling us to gain a process level understanding of the distributed moist soil plant conditions which prevail under the two management practices.

Figure 2. Soil moisture and temperature sensor prototypical array as installed at the weather station site in the Grasslands Ecological Area.

Data of this year's efforts are undergoing analysis and comparisons to the prior year's data are underway in an effort to link cause and effect in terms of wetland management practices and the resulting moist soil plant species maps and overall ecological health.

Selected Professional Presentations

Fisher, Jason, X. Meng, R. Rice, C. Butler, N. Molotch, T.C. Harmon, and R. Bales. The Sierra Nevada-San Joaquin Hydrologic Observatory (SNSJHO): A WATERS Network Test Bed. American Geophysical Union Annual Fall Meeting, San Francisco, CA, December, 2007. (poster)

Burns, Josephine R. and N.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)

Collaborative Efforts

This work is part of a larger collaborative effort between the co-investigators and the following agencies: Josephine Burns, formerly of Lawrence Berkeley National Laboratory; John Beam, William Cook, Lara Sparks, and Ricardo Ortega, California Department of Fish and Game; and Ernie Taylor and Joe Tapia, California Department of Water Resources.

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Impact of Climate Change on Irrigation Water Availability, Crop Water Requirements and Soil Salinity in the San Joaquin Valley

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An assessment of potential climate change scenarios projected to the year 2100 concluded that irrigated agriculture in the western San Joaquin Valley may adapt for a wide range of climate change scenarios. Projected reductions in surface water supply are expected to be offset in part by reduced crop water requirements due to faster crop development, and by increased groundwater pumping. The model predictions indicated that groundwater pumping will likely reduce soil salinity and will not further increase land subsidence, though will increase groundwater salinity.

The objective of the project is to assess the impact of potential climate change scenarios on the sustainability of irrigated agriculture in California; particularly, potential changes in irrigation water availability, crop water requirements, groundwater pumping, groundwater levels, and soil salinity. We consider three increased greenhouse gas (GHG) emission scenarios and study the potential impacts on the agro-hydro-climatological conditions in the region up to 2100. In particular, the analysis is broken down into four main impact areas: (i) climate responses, (ii) crop responses, (iii) agricultural water and crop management responses, and (iv) hydrologic responses.

Climate responses: For each of the three GHG emission scenarios we calculated the effect of increased atmospheric CO_2 levels on future climatic variables, i.e. daily precipitation, air temperature, and reference evapotranspiration (ET), at the regional-scale of the San Joaquin Valley (SJV) using projected output from two General Circulation Models (GCM's) until the year 2100. Relative to the no-climate change scenario, we predicted for the period 2070-2099 an annual average air temperature increase of 1.5 – 5 ^{o}C, causing an increase of annual reference ET of 0 to 12%, while annual precipitation projections are not clear. Water supply projections were based on historical water supply numbers as a function of annual precipitation. Future water supply scenarios account for long-term trends in surface water supply as a function of long-term precipitation shifts, and preserve short-term statistical properties. Predicted changes in surface water supply to the entire study area for the period 2070-2099 relative to the no-climate-change scenario ranged from -25 to +12%.

Crop responses: We considered future changes in potential crop ET rates caused by (i) increased atmospheric CO_2 levels, (ii) increased reference ET, and (iii) increased air temperatures. For direct CO_2 effects on ET, we assumed that its increase by larger leaf biomass would be offset by a decrease through stomatal closure. We also accounted for the effects of projected temperature increases on crop development through the use of degree-days. Crop ET is estimated for all climate change scenarios and for various crops in the study area. Overall changes in crop ET ranged between -13 and +7%, for the period 2070-2099 relative to the no-climate-change scenario.

Management responses: We considered the following possible management responses to changes in surface water supplies and crop ET: (i) land fallowing and retirement, (ii) changes in cropping patterns, (iii) groundwater pumping, and (iv) technological adaptation. We predicted temporary land fallowing assuming it is inversely related to surface water supply, as indicated by historical fallowing during droughts in the study area. Predicted changes in land fallowing for the 2070-2099 period, relative to the no-climate-change scenario ranged from -20 to +40%. Aside from temporary fallowing we also included recent permanent retirement of agricultural land in all our predictive simulations. Predicted changes in total irrigation water requirements for the period 2070-2099 relative to the no-climate-change scenario ranged from -9 to -1%. The general decrease in crop water requirement is caused by a combination of (i) increased fallowing due to permanent reductions in surface water supply, and (ii) a decrease in crop ET by faster crop development. A comparison to changes in surface water supplies (from -25 to +12%) indicated that in some scenarios groundwater pumping will need to increase to compensate for the loss in surface water supply, despite the decrease in irrigation water requirements. Predicted changes in groundwater pumping for the period 2070-2099 relative to the no-climate-change scenario ranged from -59 to +110%. For the worst case scenario we concluded that a region-wide improvement in irrigation efficiency to 90% through improved irrigation technologies resulted in a 50% decrease in groundwater pumping.

<u>Hydrologic responses:</u> As a final step, the climate-change induced changes in crop ET, surface water supply, and groundwater pumping were used as input into a hydro-salinity model of the study area to assess resulting impacts on groundwater levels, land subsidence, soil salinity, and crop yields. This was done for 8 climate change scenarios, including a no-climate-change scenario and one that assumes a uniform irrigation efficiency of 90% by technological adaptations. Groundwater levels are largely determined by pumping rates. Predicted changes in shallow water table extent in the study area for the period 2070-2099 relative to the no-climate-change scenario ranged from -30 to +30%. These numbers indicate that there is significant uncertainty regarding effects of climate change on shallow water tables. In none of the scenarios did the computed confined groundwater levels fall below the historical maximum drawdown in the confined aquifer of 1965. Therefore, it can be concluded that climate-change induced increases in groundwater pumping (up to 110%) will not lead to significant land subsidence in the study area. Simulated soil salinity changes as a function of (i) salinity of applied irrigation water, with groundwater containing more salts than surface water, and (ii) drainage or leaching restrictions due to shallow water tables. Although scenarios differed significantly in the amount of groundwater applied, and the simulated extent of shallow water tables, soil salinity predictions do not vary greatly between scenarios, with a gradual decrease in the simulated extent of salt-affected soils. Wet scenarios resulted in less groundwater use, counteracted by a larger simulated extent of the shallow water table area. Dry scenarios used more groundwater, but caused a lowering of shallow water tables.

Overall, our results indicate that irrigated agriculture in the western SJV may adapt for a range of climate change scenarios. Possible reductions in surface water supply are partly offset by reductions in crop water demand and increased groundwater pumping. However, no significant negative effects are anticipated due to this increase in groundwater pumping, as our simulations predicted no land subsidence or soil salinity increase.

Selected Professional Presentations

Hopmans, Jan W. Sustainability of Irrigated Agriculture, Pedofract, Madrid, Spain, June 2007.

Hopmans, Jan W. Sustainability of Irrigated Agriculture in the SJV: A historical and future perspective with climate change. University of Madison, WI, September 2007.

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Bermuda Grass Yield and Quality in Response to Different Salinity and N, Se, Mo and B Rates in West San Joaquin Valley

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[2]Department of Land, Air and Water Resources, University of California, Davis
[3]George E. Brown Jr. U.S. Salinity Lab, Riverside, California

Bermuda grass production in the saline soils of California's western San Joaquin Valley can be an effective way to manage saline drainage water. Current indications from this study suggest that this practice is sustainable.

An effective way to manage saline drainage water within the San Joaquin Valley is to use it for crop production. We have demonstrated that moderately saline water can be used as the primary irrigation source for Bermuda grass (*Cynodon dactylon* (L.) Pers) while simultaneously reclaiming a severely salt-affected site. At a sodic-saline site in Kings County near Stratford, soil salinity in the upper profile (0' to 24"; 0 to 60 cm) has decreased over the 1999 to 2004 period, while drainage and other waste waters have been used to irrigate Bermuda grass pastures. Beef cattle have been grazed yearly without adverse health effects while gaining weight at economic levels. Leaching fractions measured over the 2001 to 2004 seasons have been less than 10% of applied water. All indications are that the reuse of moderately saline waters for irrigation of a salt tolerant grass is sustainable.

Bermuda grass forage quality during this period has been measured, and yields and intake by livestock estimated under the varying grazing pressure achieved by the farmer-cooperators of the project. Because grazing pressure and management have varied each year depending on the number of cattle placed on the pastures and length of grazing season, estimates of pasture productivity are confounded with grazing management. Pasture fertilization also has varied, but has generally been less than 100 kg /ha. To estimate the potential productivity and livestock carrying capacity of pastures irrigated with saline water on salt affected sites we studied the influence of salinity and fertility on potential grass productivity and forage quality. We are measuring the response of Bermuda grass to different rates of N fertilizer at our field research site in Kings County and in a greenhouse trial at UC Davis (Figure 1).

Figure 1. Greenhouse trial at UC Davis.

On the field we selected sites with approximately average root zone salinity (0-60 cm) of 7 (S1), 14 (S2) and 21 (S3) dS/m. The same soils were used to grow Bermuda grass on the greenhouse trail. The fertilization rates were equivalent to 0 (N0), 300 (N1) and 600 (N2) kg N/ha. Soils from these sites were also collected in 60 cm deep containers and transported to UC Davis, then planted with common Bermuda grass and irrigated with saline water. Containers are being used to provide more exact control of irrigation and to allow weekly measurements of growth rates and phenological development. At the field site, exclusion cages were placed in the pastures to keep grazing cattle from disturbing the experiment at each of the three sites and each set of cages was fertilized with N similar to the pot experiment. While work is on-going at both the field and greenhouse sites, preliminary results obtained from the first harvest in the greenhouse site (Table 1 and Figure 2) show a clear effect of salinity and N on the yield and quality of the forage.

Table 1: Bermuda grass Yield and Quality: Greenhouse trial.

Treatment	Weight (gr)	Leaves (%)	Stems (%)
S1N0	27.03	56.73	43.28
S1N1	23.60	58.23	41.78
S1N2	34.30	54.08	45.93
S2N0	33.28	50.78	49.23
S2N1	21.53	51.88	48.13
S2N2	33.30	51.15	48.85
S3N0	24.63	55.28	44.73
S3N1	19.88	56.35	43.65
S3N2	19.28	58.10	41.90

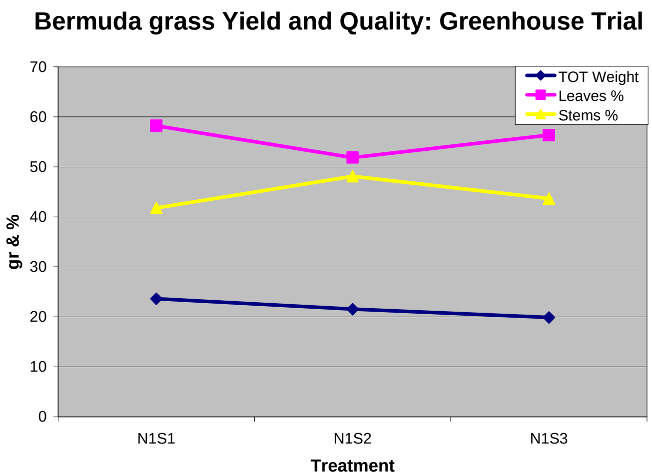

Figure 2. Average weight (gr) and proportion of leaves and stems (%) of the treatments

Despite a lack of any observed effects of trace elements on the health and growth of cattle in our experiments, the accumulation of trace elements at potentially toxic levels remains a possible limitation for the use of pastures and hay crops in managing saline drainage waters. The research site in Kings County used for these studies has areas with elevated levels of Mo in soils and drainage water but unlike some other areas in the western San Joaquin Valley, Se is deficient. In the 2008 growing season, we will add Se, B and Mo to subplots within each N treatment main plot to provide a wider range of these trace elements in soils than occur at the site naturally. The same conditions will be replicated on the green-house trial. Samples collected in 2007 are being analyzed for trace element content and will be used as a baseline for com-parison. This will allow for a systematic assessment of the capacity of Bermuda grass to accumulate these trace elements as a function of pasture productivity, salinity, and trace element content. There is little systematic information of this sort in the literature upon which to base reasonable predictions about forage productivity and quality performance under variable field conditions. Such information is essential to help make the widespread use of saline drainage water as a means of managing salinity in the San Joaquin Valley feasible.

Professional Presentations

Alonso, Maximo and Stephen Kaffka, Modeling Bermuda grass yield and quality in the western San Joaquin Valley of California, American Society of Agronomy, 2007 International Annual Meeting, New Orleans, LA, November 2007.

Alonso, Maximo, Dennis Corwin, Stephen Kaffka, and John Maas, Modeling yield and quality of Bermuda grass irrigated with saline drainage water, Salinity Forum 2, Adelaide, Australia, March – April 2008.

Collaborative Efforts

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Impacts of Delayed Drawdown on Aquatic Biota and Water Quality in Seasonal Wetlands

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Compliance with San Joaquin River water quality objectives may be improved by modifying wetland drawdown schedules to better coincide with San Joaquin River assimilative capacity. For salt, assimilative capacity is highest mid-March to mid-April when reservoir releases are made to aid salmon migration. Project data collected to date show phytoplankton concentrations can increase rapidly during the delayed drawdown period. Algae-grazing invertebrate densities also increased but not enough to completely suppress algal concentration increases.

The 178,000-acre Grassland Ecological Area in California's San Joaquin Valley is managed to provide over-wintering habitat to waterfowl on the Pacific Flyway. The major management activity is the fall flooding and spring drawdown of wetlands, timed to optimize the availability of forage vegetation and invertebrates for ducks and shorebirds. Wetland drainage contains salt, boron, and trace elements that are largely derived from imported surface water but concentrate during storage in the wetland impoundments and contribute to occasional water quality violations in the San Joaquin River (SJR) during dry years. Compliance with water quality objectives may be improved by timing wetland drawdown to coincide with high SJR salt assimilative capacity during mid-March to mid-April when reservoir releases are increased to aid salmon migration.

However, delaying wetland drawdown to improve compliance with SJR salinity objectives may have unintended impacts on the quality of the wetland resource for waterfowl overwintering. This project supplements a much larger scale, multi-year Modified Hydrology Study led by Grassland Water District (GWD), Lawrence Berkeley National Laboratory and the Department of Fish and Game (DFG) that is studying the impacts of delayed wetland drawdown on water quality, moist soil plant productivity, and wetland ecology. The current project attempts to quantify the rate of algae biomass increase during the delayed drawdown period and determine the factors that affect final algae biomass concentrations at selected sites within the study area. A complementary goal is to develop a rapid, repeatable field methodology for assessing algal ecology with minimum disturbance to wetland function. During the study, we have measured concentrations of phytoplankton and factors likely to control phytoplankton concentrations such as grazing invertebrate densities, nutrient concentrations, insolation, turbidity, temperature, and flushing rate.

The experimental sites chosen were three of six pairs of matched wetland basins (20-100 acres each) that are part of the larger Modified Hydrology Study. The wetlands selected were within the DFG Mud Slough (MS) and Los Banos (LB) Wildlife Management Areas and in the Ducky Strike (DS) Duck Club (within GWD). For each wetland pair, one was managed with a traditional March drawdown (MS-T, LB-T, DS-T); while for the other, drawdown was delayed up to one month (MS-D, DS-D, LB-D) to coincide with the period of high SJR assimilative capacity. Soil and water column samples were collected during the flooded periods at the inlets, outlets, and along transects. The transect lengths were limited to 100 m from shore in order to minimize bird disturbance; thus a majority of the wetland area could not be sampled. Data were stratified by vegetative cover, operating water depth, and hydraulic characteristics. Water quality analyses included total/volatile suspended solids, nitrogen (NH_4^+, NO_2^-+NO_3^-, organic), phosphorus (total, PO_4^{3-}), total organic carbon, alkalinity, turbidity, temperature, and pH. Planktonic and benthic invertebrates were identified and enumerated.

Data were collected between February and April, 2007. Identified phytoplankton were predominantly chlorophytes and diatoms. Zooplankton that feed on phytoplankton were found in abundance. Benthic invertebrates were also assessed to help explain the differences in algal concentrations between ponds. Microalgae concentrations increased substantially in MS-D and DS-D during delayed drawdown (170% and 320%), as did planktonic invertebrate densities (110% and 390%). Benthic invertebrate densities rose 40% on average. LB-D results did not match the other delayed drawdown wetlands; microalgae concentrations decreased 47%, while planktonic invertebrate densities increased approximately 4%.

For MS and DS, nutrient concentrations decreased during the delayed drawdown period, counter to salinity trends. NO_2^-+NO_3^- nitrogen concentrations were reduced in MS-T, MS-D, DS-T, and DS-D during the traditional flooded period; LB-T decreased, while LB-D remained unchanged. NO_2^-+NO_3^- nitrogen concentrations continued to decrease in all three wetlands during the delayed drawdown period. PO_4^{3-} phosphorus concentrations increased during the traditional flood period, while they decreased during the delayed flood period.

Of the factors potentially limiting phytoplankton concentrations, invertebrate grazing was likely the most important. Nutrients were not limiting in either the traditional or modified wetlands, as indicated by sufficient N and P of the algae. Likewise, inorganic C was not limiting, as indicated by pH (most <8.5 pH). Sunlight intensity was not significantly attenuated by water depth or turbidity.

A goal of the project is to develop a simple model of phytoplankton concentration in delayed drawdown wetlands that can be used with historical weather data to produce expected water quality probability distributions. Based on the results of the first year of sampling, three characteristics of the delayed drawdown wetlands suggest that such a simple model will be successful: (1) the short duration of the delayed drawdown period, (2) the presence of surplus nutrients, and (3) the predominantly batch-mode hydraulics of the wetlands. Although important, the density of algae grazing invertebrates appears to track the concentration of phytoplankton and thus may not need to be included as a variable. Vegetation density may be an important factor and requires further study.

Conclusions: Delaying wetland drawdown is one of several practices available to better manage salt in the SJR – the true merit needs to be assessed by measuring the direct and indirect secondary impacts of its implementation at all levels of the wetland ecosystem. In terms of the phytoplankton impacts, although wetland ecosystems are complex, a relatively simple model of phytoplankton concentration during delayed drawdown may be successful. Along with other information from the larger Modified Hydrology Study, an improved understanding of the consequences of delayed drawdown on wetland water quality and aquatic biota would help determine when and where delayed drawdown might be employed with minimal risk to wetland and river ecosystems.

Collaborative Efforts

This project is part of an interagency effort to study water quality and ecological impacts of delayed drawdown in the Grassland Ecological Area. Contributors to our research include John Beam, William Cook, and Ric Ortega of DFG, Laura Sparks of GWD, John Eadie of UC Davis, and Josephine Burns of Lawrence Berkeley National Laboratory.

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Salt Dynamics in Non-Riparian Freshwater Wetlands

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We have investigated 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. The role of year-over-year storage of salts in the soil column has been explored using a combination of field, laboratory and numerical analysis.

We have investigated 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. Over the two years of this grant, we performed both field and laboratory experiments and developed a numerical analysis to simulate the laboratory experiments.

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 (Figure 1). 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. Several interesting features have emerged from the analysis of this data. As would be expected, the dynamics of the wetland are dominated by wind forcing and heating and cooling at the surface. At the same time, however, the salinity dynamics are strongly influenced by management decisions involving the draw-down of the wetland (Figure 2).

Figure 1. Deployment of field instruments in Curlew Flat wetland. Graduate student Kate Huckelbridge is shown.

The laboratory experiments we 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.

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

To aid in the interpretation of the laboratory results, and to extend them to an estimate of the flux of salt from the soil column into the water column, we pursued a numerical model of the soil-water columns studied in the laboratory. A one-dimensional advection-diffusion model that allows a spatially-variable diffusion to be specified was developed and driven by the laboratory observations. We found that the observations were internally consistent and the numerical calculations could easily match the observed trajectories. As a result, we used the numerical simulations to extend the observations spatially to the soil-water interface and calculate the flux of salts between the soils and the water column (Figure 3). Although many of these results are still being analyzed, it is already clear that the details of wetland flood-up and draw-down play a part in establishing the year-over-year salinity dynamics.

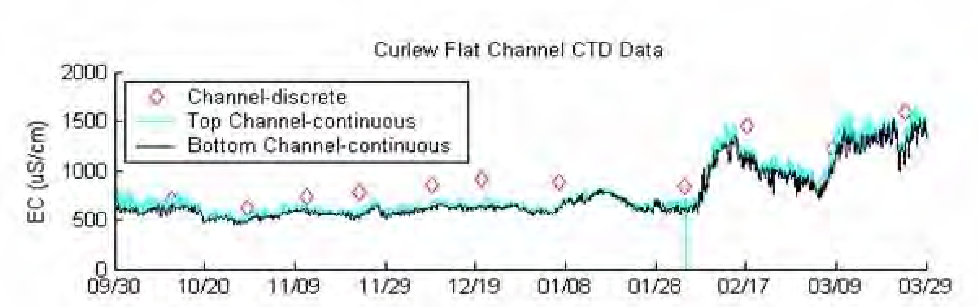

Figure 2. Seasonable variability of electrical conductivity (as surrogate for salinity) during flooded period. Increase in conductivity in early February followed a rapid draw-down of the wetland by managers.

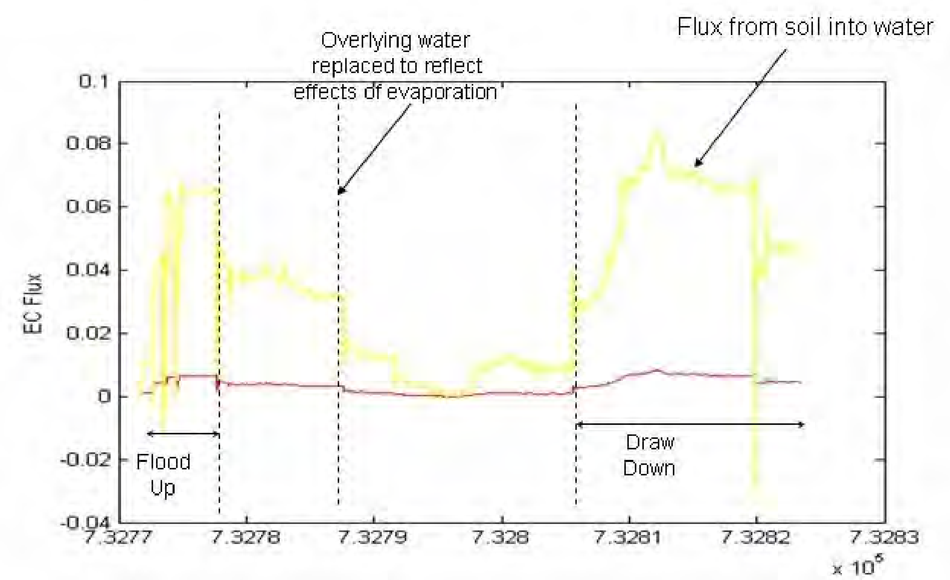

Figure 3. Numerical flux calculations based on laboratory experiment for fast flood-up, slow draw-down.

Professional Presentations

Huckelbridge, K., Salt Dynamics in Freshwater Wetlands, UC Davis, Civil & Environmental Engineering, May, 2007.

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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Sustainable Ecosystems under Land Retirement

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The retired land area in the western San Joaquin valley can be developed as wildlife habitat to improve the ecological system without any serious negative consequences under certain combination of soil type and shallow water table conditions.

Use of intensive irrigation in arid and semi-arid areas usually leads to gradual salinization of the soil detrimental to crop-yields. The salinization problem is mitigated by applying irrigation in excess of crop requirements, which leaches the excess salt load to the groundwater. Lack of appropriate natural or man made drainage systems to dispose off this excessive saline recharge to the groundwater leads to a gradual rise in the water table eventually encroaching upon the root zone. This may ultimately make the land unfit for any productive economic activity. The abandoned land may even lead to desertification with adverse environ-mental consequences. In closed drainage basins, land retirement has been proposed as a management tool to address this problem. Land retirement essentially entails intentionally discontinuing irrigation of selected farmlands with the expectation that the shallow water table beneath those lands should drop and the root zone salinity level should decrease.

In the San Joaquin Valley of California, intensive irrigation in conjunction with a shallow underlying layer of clay, known as the Corcoran clay layer, and absence of a drainage system caused the root zone to become highly saline and shallow water table to rise. Land retirement would remove from production those farmlands contributing the poorest quality subsurface drain water. Based on numerical models results, it was expected that with land retirement of substantial irrigated lands with poor drainage characteristics, beneath which lies shallow groundwater with high salt load, the shallow water table beneath those lands should drop. A part of the retired lands could also be used for wildlife habitat. A potential negative side of the land retirement option that has to be considered is that in certain evapotranspiration enabling soil and water table conditions, water will be drawn upwards and evaporated, leaving a deposit of salts on the surface and in the root zone. The deposits of salt on the surface may then be wind blown to adjacent areas creating a potential environmental hazard.

Using field results from the Land Retirement Demonstration Project at the Tranquillity site in western Fresno County, operated by the U.S. Department of the Interior, principles of mass balance in a control volume, the HYDRUS-1D Software Package for Simulating the One-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media, and PEST, a model-independent parameter optimizer, we have investigated the processes of soil water and salinity movement in the root zone and the deep vadose zone. Various combinations of evapotranspiration, soil water retention properties, water table condition and top and bottom boundary conditions yield different results. We show that it is feasible to use Land Retirement to decrease shallow water table and soil water salinity and develop native plants as a means to facilitate habitat restoration for certain combinations of soil and bottom boundary condition. In certain other combinations of factors, land retirement may not be the best option available.

Professional Presentations

Singh, Purnendu, Wallender Wesley, Land Retirement as a Habitat Restoration Tool, AGU Fall Meeting, Poster Presentation, San Francisco, CA, December 2007.

Collaborative Efforts

Collaborative contributions 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 Tranquillity 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.

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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, but generally focused on water conservation and improving 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.

Using Regulated Deficit Irrigation to Increase Almond Production and Water Productivity

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We have reduced consumptive use of mature almonds by up to 29% using RDI with only a modest decrease in kernel yield (7%), due almost entirely to smaller kernels. The goal is to eliminate any yield reduction by increasing the fruiting density of the RDI trees.

Traditional water conservation efforts involve improving application efficiency and making use of scientific irrigation scheduling. These approaches reduce losses due to deep percolation below the root zone of the plant and runoff from the end of the field (tailwater). Unless these "losses" move to saline sinks, they are not net losses since they can be reused. On the other hand, any reduction in evapotranspiration (ET) results in reduced consumptive use and a true saving of water. Since transpiration (T) is by far the largest component of ET, it needs to be the focus of any technique to reduce consumptive use. However, when T is decreased by water deficits, crop production in most herbaceous crops is also reduced below its maximum potential. Happily, this is not necessarily the case for tree crops. A growing body of work worldwide shows that consumptive use can be reduced in orchards without negative impacts on production. The approach is to use regulated deficit irrigation (RDI); purposely stressing the trees during stress tolerant periods of the season. Our previous RDI work with almonds using preharvest stress showed that fruit load could be maintained even though the trees were smaller due to less vegetative growth. In other words, we achieved higher fruiting density. This suggests that kernel production per unit of land could be increased while reducing the consumptive use of water.

We are testing this hypothesis in a commercial orchard located near McFarland in the southern San Joaquin Valley. The test orchard was selected since it has two planting densities in adjacent blocks; high density (21 x 18 ft) and low density (24 x 21 ft). We need to compare different planting densities since a key component of our hypothesis is that higher density trees are subject to adverse shading impacts that could reduce fruit load and that RDI could lessen foliage density, allowing more light penetration and thus, improve fruiting. The experimental orchard is planted with cv. Butte and Padre in a 1:1 row pattern. Each of four replicates is four rows wide and 39 trees long with the interior two rows used for measurements. Each replicate contains both cultivars. The cooperators' micro-sprinkler irrigation system was modified to allow us to impose preharvest stress in the RDI treatment rows. In addition to our applied water measurements, neutron probe readings are used to estimate the extraction of soil water between the beginning and end of the season that, in turn, allows for the calculation of consumptive use.

Applied water during 2006 in the high density RDI and fully irrigated Control trees was 27.2 and 37.7 inches, respectively, a 28.4% reduction. Equivalent data for the low density trees was 31.0 and 42.0 inches, respectively; 26.2% less for the RDI. Similar differences were calculated for consumptive use values. Midday shaded leaf water potential, a measure of tree stress, showed that the RDI trees were indeed stressed during much of the preharvest period relative to the Control. The

Table 1. Yield, yield component, and water productivity data for 2006.

Planting Density	Almond Cultivar	Irrigation Regime	Kernel Dry Weight (g)	Kernel Percentage (% by Wt.)	Nut Load (No./tree)	Kernel Yield 5% H2O (lb/acre)	Applied Water Productivity (lb/inch)	Consumptive Use Water Productivity (lb/inch)
High High	Butte Butte	RDI Control	0.830 a* 0.920 b	35.6 36.5	11710 11550	2502 2690	92.0 a 71.3 b	75.6 a 58.8 b
				NSD**	NSD	NSD		
Low Low	Butte Butte	RDI Control	0.775 a 0.870 b	35.1 34.6	11740 12600	2321 a 2783 b	74.9 66.3	63.8 58.3
				NSD	NSD		NSD	NSD
High High	Padre Padre	RDI Control	0.847 a 0.972 b	28.2 a 29.5 b	12470 12700	2680 a 3133 b	98.5 a 83.1 b	81.0 a 68.6 b
					NSD			
Low Low	Padre Padre	RDI Control	0.850 0.910	28.1 a 29.6 b	11970 12870	2577 2981	83.2 a 71.0 b	70.8 62.5
			NSD		NSD	NSD		NSD

* Values followed by different letters are statistically different using Fisher's LSD Method at the 5% confidence level. Statistical analysis was done between the irrigation treatments (RDI and Control) for each planting cv. and planting density.

** NSD indicated no statistically significant difference.

maximum difference between treatments was in early July with RDI and Control readings of about -2.2 and -1.2 MPa, respectively. Padre trees were slightly more stressed than Butte but the differences were consistent.

Individual kernel weight was always lower for the RDI regime, regardless of cv. or planting density (Table 1), with mean reductions of about 10%. Kernel percentages were lower for the RDI trees only with the Padre and by an average of about 4%. Nut loads were not significantly different between treatments for either cv. or planting density. However, the differences between irrigation regimes were less for the high than low density trees. This seems to support our hypothesis. Kernel yields were lower for the RDI treatments due mostly to the aforementioned smaller fruit. The least reduction occurred in the high density Butte (7.0% lower than the Control) and the most in the low density Butte (16.6% lower than the Control).

The high density plantings with RDI for both cvs. had higher applied and consumptive use water productivities relative to the Control. High density applied and consumptive use water productivity was about 29 and 18% better than the Control for the Butte and Padre cvs, respectively.

It is not possible to draw conclusions with a single year of data. However, we are encouraged that fruit loads are being maintained in the RDI trees while water productivities are higher.

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Reducing Water Use in Navel Orange Production with Partial Root Zone Drying

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From 1 July 2007 to 20 September 2007, partial root zone drying (PRD) treatments delivering 25% and 40% less water per irrigation than the well-watered control reduced the total amount of irrigation water applied to 'Washington' navel orange trees by 41% and 45%. A conventional irrigation treatment delivering 40% less water than the control reduced the amount of irrigation water applied relative to the control by 55%. The effect of these differences in water-use on yield, fruit size and quality will not be known until our first harvest in January 2008.

The California citrus industry produces "picture perfect" navel orange fruit for the fresh fruit market on 124,385 irrigated acres. The cost of irrigation water is a major expense associated with citrus production. Regulated deficit irrigation (RDI) and partial root zone drying (PRD) are irrigation strategies designed to increase water-use efficiency in fruit tree crops to further reduce production costs. Both methods limit vegetative shoot growth in favor of crop development with the goal that neither the current nor return yield is negatively affected. With RDI, water deficit is applied in an orchard in a carefully controlled manner during a specific period in the phenology of the tree. When using RDI, timing is critical. In contrast, PRD is the practice of alternately wetting and drying the root zone on two sides of the tree and is employed year-round.

Our research goal is to test the feasibility of using partial root zone drying (PRD) to reduce the amount of water used in citrus production and, thus, increase grower net income.

From 1 July 2007 to 20 September 2007, partial root zone drying (PRD) treatments delivering 25% and 40% less water per irrigation than the well-watered control reduced the total amount of irrigation water applied to commercially bearing 'Washington' navel orange trees 41% and 45%. A conventional irrigation treatment delivering 40% less water per irrigation than the control reduced the amount of water applied relative to the control 55%. The effect of these differences in water-use on yield, fruit size and quality will not be known until our first harvest in January 2008.

This is Block 13 at UCR Citrus Research Center and Agricultural Experiment Station - data logger recording soil moisture content measured by in ground soil moisture meters. The data are used for scheduling when and how much water to apply to 'Washington' navel orange trees in the partial root zone drying (PRD), reduced conventional irrigation (CI-RR) and control irrigation (CI) treatments.

Our results, thus far, are consistent with results obtained using PRD in commercial sweet orange production in Australia. In a 4-year field study, 40% less water was applied by PRD than the fully irrigated control with no significant effect on fruit number, size or quality, (Loveys et al. 2000. Acta Hort. 537:187–197).

Block 13 at UCR Citrus Research Center and Agricultural Experiment Station - controls for applying the partial root zone drying (PRD) and reduced conventional (CI-RR) and control irrigation (CI) treatments to 'Washington' navel orange trees.

Collaborative Efforts

The contributions of the UC Riverside Agricultural Operations staff (staff leaders, Steve Cockerham, Sue Lee, Lynn Morrison and Dan Bowles) to the success of our Prosser Trust project were critical. The Agricultural Operations team did an excellent job in designing and installing the complex irrigation system - multiple lines, valves, regulators, flow meters and timers - that was required for us to conduct our research with the precision and number of treatments and replications prescribed. When we took over the system, they had it all clearly labeled, color-coded and conveniently organized. Our thanks for a job well done.

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Toward Improved Irrigation Efficiency through Real-time Assimilation of Multi-spectral Satellite Remote Sensing Data into Crop Models

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The amount of water used for agriculture in California consumes the majority of the total water supply. Since estimation of irrigation demand of crops can be difficult, the process can be inefficient and therefore an area where significant water savings may be possible. In this work, a data assimilation method combining dynamic crop models and remote sensing observations is proposed to identify necessary irrigation over large regions.

The amount of water used for agriculture in California consumes 40% of the total water supply and 75% of the developed water supply. With agriculture using most of California's developed water supply, this is the most likely arena where water conservation could be implemented. In irrigated agricultural regions, over-watering is often a problem, resulting in potentially large runoff volume containing a high concentration of contaminants. In this work, a method combining dynamic crop models and remote sensing observations is proposed to identify necessary irrigation over large regions.

Ecological process models (agricultural crop models) dynamically evolve vegetation and can predict the necessary irrigation rate to optimize crop yield. These types of models require meteorological and soils data, which can be erroneous and lead to prediction uncertainty. To reduce the amount of uncertainty, a technique of assimilating observational data with agricultural process models will be used to more effectively simulate agricultural water requirements.

Observational data on the scale required for agricultural irrigation management is only available via remote sensing platforms. Remote sensing data does not measure crop or water states but rather reflectance or brightness temperature at the surface. Using a radiative transfer model coupled to the crop model allows for assimilation of the remote sensing observations to update model state estimates.

Data assimilation methods, e.g. the Ensemble Kalman Filter (EnKF), have been used previously in hydrologic applications to estimate soil moisture and snow water equivalent. The EnKF will determine the relative uncertainty of the modeled and observational data and provide an optimal estimate of the vegetation and soil moisture states. The goal of this project is to determine the feasibility of estimating irrigation water to apply to a crop stand via the assimilation of visible and near infrared remote sensing observations into a physically based crop model using the EnKF.

Thus far our work has focused on the selection and testing of the proper agricultural and radiative transfer models, which include the Decision Support for Agrotechnology Transfer Cropping System Model and PROSAIL radiative transfer model.

Two agriculturally important regions within California were selected. The first region is a coastal agricultural region in Ventura County, Oxnard, CA and the second region chosen is in Imperial Valley, an inland, semi-arid agriculturally important region. Meteorological stations are located near both sites and a University of California research station is also located at the Imperial Valley site.

Initial testing of the DSSAT-CSM model has been performed. Analyses of different modeling options were explored in four different irrigation implementations. Five seasons of data (2002-2006) were simulated. The four different experiments were analyzed to confirm that the output of the model provided realistic predictions of model states.

Preparation has begun on for identifying the sections of DSSAT-CSM that will need to be modified for use in the data assimilation scheme. Output from DSSAT-CSM will be used as input to PROSAIL in the data assimilation framework.

During the next year, the data assimilation framework will be built by coupling the crop and radiative transfer models within the EnKF code. Once this is completed, observing system simulation experiments (OSSEs) will be performed to test the feasibility of estimating the soil moisture and vegetation states so that irrigation could be optimized.

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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 traditionally grown Upland cotton plantings,* Gossypium hirsutum*, previously used for irrigation studies. This research develops deficit irrigation strategies and points out opportunities for improving water use efficiency leading to higher productivity per unit of water applied.*

The 2007 growing season was the first season on record to find California growers producing more Pima cotton, *Gossypium barbedense*, than its traditional Upland counterpart, *Gossypium hirsutum*. Though Pima cotton was first grown experimentally in California during the 1920's, it was not 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 extra-long staple (ELS) Pima cotton have led to Pima cotton acreage increasing to 270,000 acres with Upland plantings declining to 170,000 acres in 2007. Combined irrigation water applications for these two crops are estimated at over 1.3 million acre feet statewide, and options to reduce applied irrigation water without adversely impacting crop productivity are needed.

Pima cotton's indeterminate growth habit has led growers and researchers to suspect that its water use characteristics were different from those of more traditional plant types and work began to document changes in crop water use. The work conducted in this study is aimed at developing additional crop water use information for Pima cotton, validating the water stress guidelines that have been proposed for the crop, increasing irrigation management extension outreach activities, and documenting the value and potential for 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.

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 focused our activities at the WSREC site. Our 2006 season irrigation studies incorporated a range of applied irrigation volumes in three irrigation treatments which enabled us to evaluate water deficit treatments as well as low water stress irrigation treatments that would optimize yield. Preirrigation activities in late February allowed an application of about 12 inches of water which largely went to refilling the soil water profile that was deficient of water due to the previous crop. Additional in-season irrigations of approximately 6 inches each were applied to the field including two, three and four post-plant irrigations that represented the range of water stress conditions desired.

The 2006 cotton growing season was characterized by good planting conditions that were accompanied by optimal plant stands; the slight delays in early season plant growth caused by cooler than average spring conditions did not have much impact on yield expectations though first flower date was delayed several days beyond the long-term average. The most significant event during the season came during the month of August when mid and late August daily temperatures typically exceeded 110 degrees, leaving the flowering cotton's pollen susceptible to heat stress events. This is widely thought to have played an important role in reducing yields below the 5 year average.

The timing, duration and magnitude of water stress, as measured by the pressure chamber, was found to be a very useful tool in scheduling irrigation events and determining when crop water stresses are significant enough to impact yield. Cumulative leaf water potential readings confirmed that the timing of the two in-season irrigation events assisted in minimizing crop losses from excessive water stress. Determining the appropriateness of the deficit irrigation treatment timing was also confirmed by the yield results obtained.


Pressure chamber

For each of the three cotton types evaluated in this study, Pima, Upland and the interspecific Pima-Upland hybrid, water deficit treatments performed exceedingly well when compared to the irrigation treatment that followed UCCE irrigation management guidelines. Surprisingly, a larger impact to productivity was observed between the widely grown plant types tested in this study. The Pima cotton exhibited high productivity relative to the Upland and interspecific hybrid. While numeric yield reductions were observed in the deficit irrigation treatments, there were no significant impacts on crop yield when comparing the guideline treatments with the deficit irrigation treatment. Lower yield was only observed in the excessive irrigation treatment compared to the guideline treatment. 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. Deficit irrigation practices in cotton can be developed as a method 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 would like to thank Kevin Collins of Borba Farms and Tom Fairless of Fairless Farms for their time and resources while conducting field activity on their farms. We also acknowledge the invaluable support of UC 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 in the San Joaquin Valley (SJV) have seen water costs increase 3 to 5 fold in the last ten years, while dependable supplies have decreased. Growers of low value field crops like cotton are looking for alternative crops and water supplies. Some marginally saline drain and groundwaters associated with over 250,000 acres of the westside SJV can be used to increase water supply and decrease costs for irrigating salt tolerant crops. This study is testing the economic and cultural viability of establishing a large, commercial-scale pistachio orchard interplanted with cotton using saline irrigation water.

Work in Iran, a 2001 salt tank study at the USDA Salinity Lab, Riverside, and a small plot, 9-year study (ending 2002) 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 sub-surface drip tape. The fields were well reclaimed (salinity averaged 1.57 dS/m to 3 feet) and had good drainage. We used fresh (Aqueduct), blended (Blend) 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. In 2005, pistachio rootstocks (PG1) were planted in March, 17 feet apart on a 22 foot row spacing and interplanted with four 38 inch rows of pima cotton. Pistachios were budded with a Kerman scion in July. 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 total based on a 9.5 foot wide area (7.8 inches for the 22 foot row spacing). Cotton was not interplanted for 2007 as the grower stopped all his Westside cotton production due to severe shortage of canal water.

Plant tissue analysis showed a significant 0.5 to 3 fold increase in chloride and boron levels in both cotton and pistachio tissues (Table 1), but produced no toxicity symptoms. Pima cotton lint yields were nearly 4 bale/acre in 2004, but crashed to about 2 bale/acre in 2005 due to very cool spring conditions that made for poor stand establishment. Yields and plant height were unaffected by salinity. Spring 2006 provided excellent conditions for cotton growth, but excessive salts accumulated in the top 4 inches of the Well treatment beds reduced cotton emergence by 14% (statistically insignificant). Plant height, however, was significantly reduced early in the season, but this difference was insignificant by the end of July. Comparing aerial imagery and the Normalized Difference Vegetation Index (NDVI) for August 2004 and 2006 also showed no treatment impacts. Lint yield, however, was reduced by 275 lb/ac compared to the Aqueduct water, but still excellent at 3.12 bale/ac. Increase in pistachio rootstock diameter and general tree development has been unaffected by salinity.

Salinity and sustainability: At the end of 2006, after three seasons of cotton irrigation, this program has applied about 6,900, 32,500 and 54,000 lb/ac of salt in the Aqueduct, Blend and Well treatments, respectively. Average rootzone salinity to 5 feet has remained surprisingly stable at about an EC_e of 2.5 dS/m for the Aqueduct and 4.6 dS/m for the Well treatment. However, in-season EC_e in the top three feet is much higher. Without 6 to 10 inches of effective rainfall or fresh water winter irrigation for efficient leaching this system may not be sustainable. The other uncertainty is the long-term fate of currently adsorbed boron. This soil has a huge fixation capacity, with a native total B content of 22 ppm. Current levels of soluble B, however, are only 2.5 ppm in our Well treatment. This concern, plus the decrease in cotton yield in 2006, combined with a nearly 20% increase in the Well water EC over the last four years has prompted the grower to insist that salinity treatments be cut in half of current levels as he is concerned for this long-term 310 acre investment. We will report on these changes next year.

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

	Cl (%)	B (ppm)	Root-zone EC_e to 5 ft (dS/m)	[1]Cotton Ht, Pistachio Circum (inch)	Cotton Lint Yield (lb/ac)	[2]Total Salts Applied in Irrigation (lb/ac)
2004 **Cotn Petioles 8/27**			**10/6/04**	**9/14/04**	**10/6/04**	**Cotton'04**
Aque	2.58	34	2.71	42.2	1933	2,343
50/50	**3.23	37	*4.08	*35.8	1928	11,390
Well	*3.00	37	*4.68	38.8	2016	21,444
2005 **Cotn Petioles 9/15**			**10/18/05**	**9/15/05**	**10/19/05**	**Cotton'05**
Aque	2.71	42	1.42	41.6	954	2,305
50/50	*3.13	46	3.71	43.1	1129	10,144
Well	**3.38	**50	*4.74	42.1	999	16,975
Pist Leaves 9/15			**10/18/05**	**10/19/05**		**Pistach'05**
Aque	0.27	194	2.87	2.31		1,742
50/50	0.27	**492	4.12	2.17		8,570
Well	**0.38	**673	*4.44	2.18		14,782
2006 **Cotn Petioles 9/21**			**10/30/06**	**9/21/06**	**10/27/06**	**Cotton'06**
Aque	1.95	48	1.01	44.9	1835	1,967
50/50	1.91	55	*3.61	45.0	1615	11,046
Well	2.21	*56	**4.63	40.9	*1560	15,832
Pist Leaves 10/31			**10/30/06**	**10/19/06**		**Pistach'06**
Aque	0.52	531	2.65	2.58		1,022
50/50	*0.58	**954	4.34	2.55		8,994
Well	*0.62	**1096	*4.61	2.49		11,104
2007 **Pist Leaves 6/19**				**4/27/07**		**Pistach'07**
Aque	0.24	167		2.68		
50/50	0.28	**315		2.66		
Well	0.30	**384		2.61		

*Significantly different from Aqueduct @ 0.05, **Significant @ 0.01
[1]Cotton height @ irrigation cuttoff.
[2]Cotton cover = 12.7 feet/tree row Pistachios = 9.3 feet/tree row

Publications

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