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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 IV – Water Development and Management Alternatives

No current projects in this category

Research Category V – Water Law, Institutions and Policy

Salinity/Drainage Program *(continued)*

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.

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, including bedrock infiltration and the role of upland bedrock areas in recharge of adjacent valley basin-fill aquifers, in the Sierra Nevada and adjacent foothills.

We have measured subsurface temperatures in the Tahoe Basin region, and are using patterns of subsurface heat flow to help trace groundwater flow. Shallow soil temperature (T) was monitored at many sites with automated sensors buried in the soil. Measurement of deeper subsurface T profiles from accessible wells consisted of lowering a high-resolution thermometer down each well and recording T measurements at every few feet of depth. Measured differences in subsurface T define subsurface conductive heat flow, which is typically perturbed by moving groundwater as it carries heat energy with its flow.

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 due to the insulating effect of snow cover. Thus during spring snowmelt, infiltration was not impeded by a layer of frozen topsoil. A dozen probes at sites close to 6300 ft elevation were left in place until fall 2007. At a few sites, soil was frozen for several days during winter 2006-07 when mean air temperature was below freezing and snow cover absent. During the warm season, soil T is very sensitive to shading by vegetative cover. Observations show warm season soil T departure from air T is determined mainly by soil moisture, solar radiation exposure, and soil surface color.

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 additionally 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 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. A major fault zone is implicated in the unusually high permeability at >800 ft depth observed in one bedrock well.

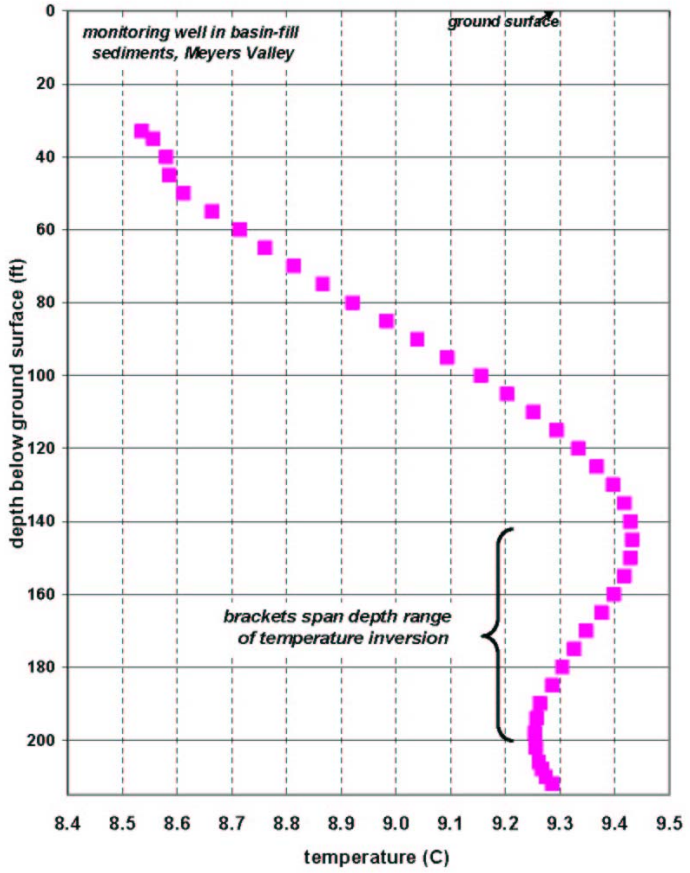

Figure 1: Subsurface temperature (T) measured at 5 ft. intervals in a monitoring well completed in basin-fill sediments in Meyers. Subsurface T typically increases with increasing depth, as does T in this well down to ~140 ft. below ground surface. However, from ~140 to 200 ft. depth, T decreases with increasing depth. An aquitard is present within the depth range of this inversion. This T profile reflects the presence of warmer lateral groundwater flow above the aquitard and cooler lateral groundwater flow below the aquitard. The cooler groundwater flow in the aquifer below ~200 ft. depth is likely sourced from locally focused groundwater recharge near the base of a mountain front.

At several bedrock wells, T measurements yield constraints on the rate of groundwater flow downward beneath the borehole bottom. For some valley wells 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 through 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 basin-fill areas, many well T-profile shapes are related to mean annual rates of infiltration of precipitation and aquitard leakage. Marked temperature inversions were found at several valley wells (figure 1), reflecting the presence of rapid lateral flow of cool groundwater. This groundwater is likely sourced from locally focused recharge near the base of mountain-fronts flanking basin-fill aquifers.

Professional Presentations

Trask, James, and Graham Fogg. Evidence for Significant Mountain-Front and Mountain-Block Recharge of Valley Aquifers in the Tahoe Basin Region. 4th Biennial Tahoe Basin Science Conference, Incline Village, NV, March 17-19, 2008.

Collaborative Efforts

Ivo Bergsohn (South Tahoe PUD hydrogeologist), and Dr. Eric Labolle (UC Davis) have developed hydrostratigraphic and calibrated 3-D groundwater flow models of the South Tahoe basin-fill aquifer system. The model range for groundwater recharge and areal flow patterns based on hydraulic data is corroborated by both heat flow patterns, inferred using the temperature data, and by spatial patterns of stable isotope levels in surface and ground water.

We also are exploring possible collaborations for additional applications of the soil temperature data set. In addition to our investigations, this data is pertinent to Sierra Nevada ecosystem change research and montane micro-meteorology.

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Comparative Inverse Modeling with Combination of Multiphysics Codes and Parameter Estimation Snap-on Tools

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Incorporation of different types of data such as piezometric head, concentration, age, environmental isotopic data, and other sources of information can improve parameter estimation and reduce non-uniqueness of inverse modeling.

Inverse problems in hydrology and hydrogeology are challenging due to non-uniqueness. One avenue to reduction of non-uniqueness involves use of multiple data sets governed by the same aquifer property to be estimated, such as piezometric head and groundwater age. Since head information is governed by a diffusion equation and age information is governed by an advection-dispersion-reaction equation, their coupling may sharpen inverse problem solutions. The coupling of piezometric head and concentration data has been used for many years to estimate groundwater hydraulic parameters. Since groundwater age is affected by the same processes as a chemical component in the water it can be considered as a tracer, thus its observation data has been used in the same way to help estimation of aquifer properties. In our study we apply multiphysics modeling of simplified, idealized problem in the forward sense to solve, simultaneously, the steady-state flow and mean age equations, the output of which is used as input to an indirect inversion scheme (UCODE-2005) to calibrate some of the parameters involved. The flow domain is drawn from a classical two-dimensional problem with three of four boundaries corresponding to no-flow conditions (Figure 1). In the inverse part, we investigate the role of sample data location on the non-uniqueness problem. We demonstrate non-uniqueness of the inverse for several different hypothesized sets of calibration data, including noise vs. no-noise cases, dense vs. sparse sampling of head and age, and nonuniform sampling densities.

Based on the results of our study, selection of appropriate observations density and observations type is important to reduce the level of calibration uncertainty (Figure 2). The addition of groundwater age observations in our study reduced the non-uniqueness of the calibration. The sampling

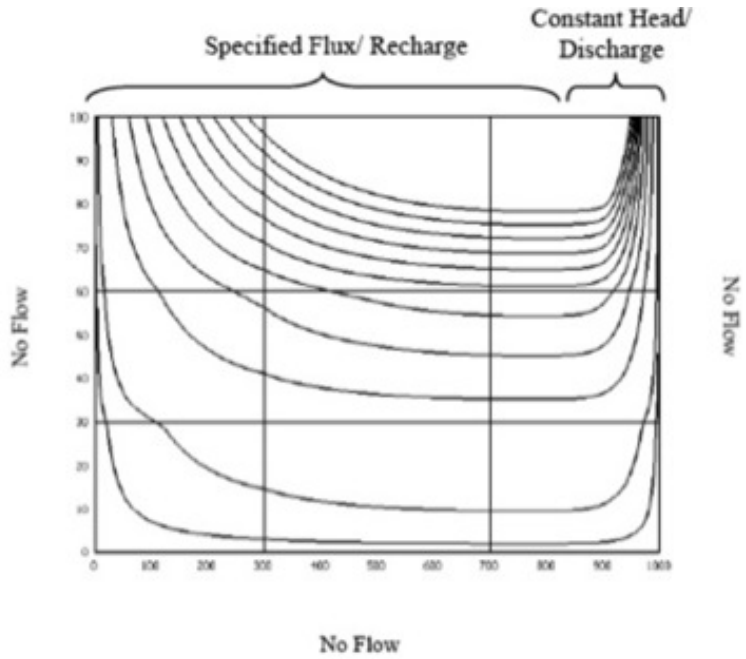

Figure 1. Flow boundary conditions and streamlines of the aquifer system.

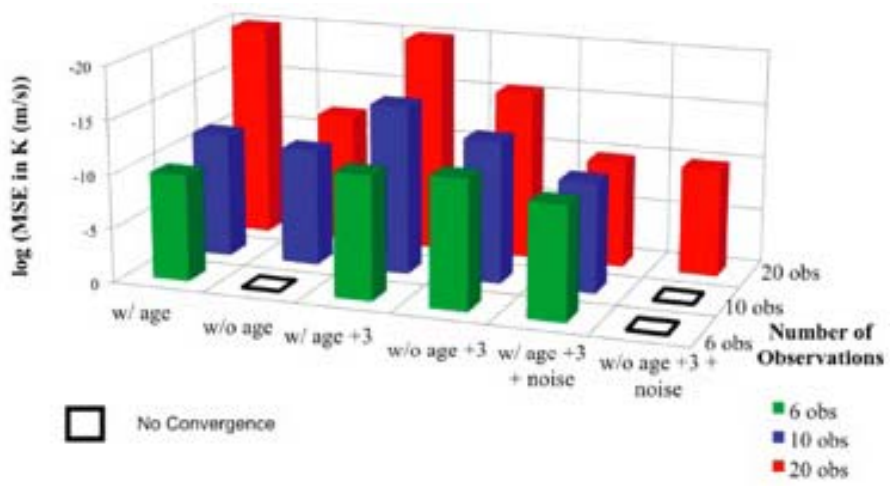

Figure 2. Histogram showing one measure of non-uniqueness, the Mean Square Error between the original true zoned hydraulic conductivities and those determined by the inversion, with the constraint that the inverse-solved values correspond to insignificant error in the head and age fields as measured in the sample locations.

density was also an important issue in our calibration; however the concentrated observation distribution was not able to overcome the non-uniqueness problem even in cases of dense sampling. Age observation was not able to eliminate non-uniqueness at locations far away from the sampling locations. Although application of distributed sampling enabled us to achieve unique estimated parameters using "true" observation values (subsampled directly from the forward solution), the same observation density/locations could not result in unique solution when random noises were added to the "true" observation values. Non-uniqueness specifically persists when the domain allows different flow fields to generate similar mean ages at sampling locations.

Publications

Mauro Giudici, Timothy Ginn, Chiara Vassena, Hanieh Haeri, Laura Foglia, "A critical review of the properties of forward and inverse problems in groundwater hydrology", Calibration and Reliability in Groundwater Modeling: Credibility of Modeling, IAHS Publ. 320, 2008.

Professional Presentations

Tim Ginn, Tim Scheibe, Hanieh Haeri, and Cynthia Mcclain, "An expanded survey of groundwater modeling practitioners about how they quantify uncertainty: which tools they use, why, and why not", GSA Annual Meeting, Denver, CO, October 2007.

Hanieh Haeri, Laura Foglia, Tim Ginn, "Comparative Inverse Modeling With Combination of Multi-physics Codes and Parameter Estimation Snap-on Tools", (1) 26th Biennial Groundwater Conference and 16th Annual Meeting, Groundwater Resources Association of California, Sacramento, CA, September 2007. (2) American Geophysical Union (AGU), San Francisco, CA, December 2007. (3) MODFLOW and more: Groundwater and Public Policy, Golden, CO, May 2008. (4) Computational Methods in Water Resources (CMWR), San Francisco, CA, July 2008

Collaborative Efforts

We are in the process of collecting data from a regional alluvial aquifer in the San Joaquin Valley, California, surrounding the Modesto city area in order to test our theoretical findings. To this aim we are collaborating with Steve Phillips from USGS who provided us with the groundwater model and part of the data available in the valley.

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Simulating and Understanding Variability in Runoff from the Sierra Nevada

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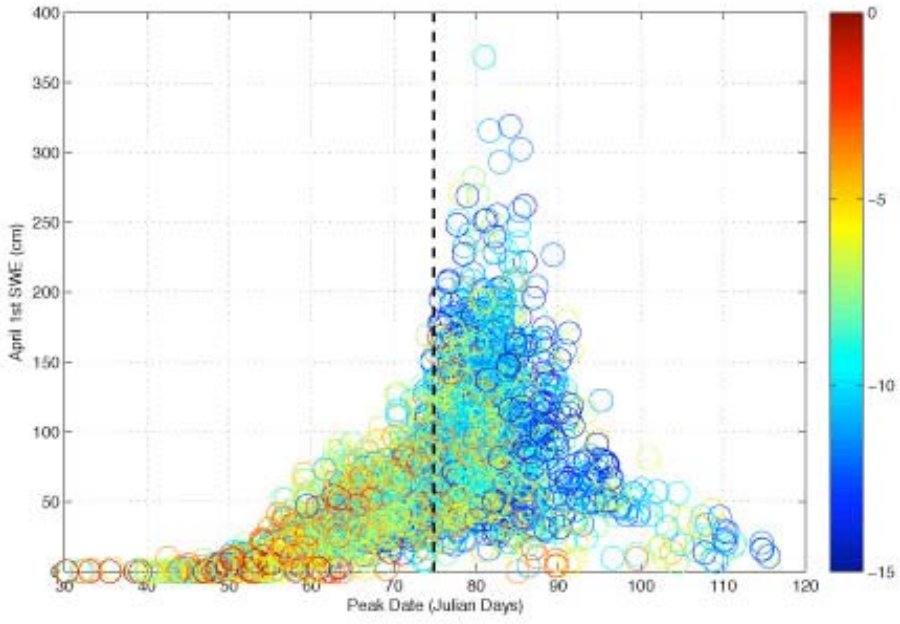
This study aims to understand the origins of recent and future changes in snowpack and runoff in the Sierra Nevada using both observational and modeling techniques. Together, observations and models indicate the snowpack will likely undergo dramatic changes in the coming decades and moreover, that those changes are already detectable and well underway.

This study aims to understand the origins of recent and future changes in snowpack and runoff in the Sierra Nevada using both observational and modeling techniques.

To study the snowpack from an observational perspective, we examined snow station observations and surface temperature data. First-of-the-month snow water equivalent measurements were combined from two data sets to provide sufficient data for statistical analysis of snowpack evolution during the snow season from 1930 to 2007. The monthly data is used to calculate peak snow mass timing to assess variability in timing and magnitude of snow accumulation and melt from February 1st to May 1st. Since 1930, there has been a trend towards earlier snow mass peak timing by 0.4 days per decade. Since 1948, regional March temperatures have also increased at a rate of 0.4ºC per decade. Statistical analysis shows that the trend in snow mass peak timing can be explained by its sensitivity to local March temperatures (see figure, which shows how closely linked March temperatures are to the peak of the Sierra snowpack). The snow mass peak timing is shown to shift earlier in the season by 1.3 days per 1ºC increase in March temperatures. Given scenarios of warming in California, we can expect to see acceleration in this trend; this will reduce the warm season storage capacity of the California snowpack.

This observational study paints a picture of a rapidly changing snowpack already responding to global climate change. These



Scatterplot of peak snow mass date versus April 1st snow water equivalent (SWE) value for 61 stations from 1948 to 2007; colored by the monthly mean local March temperature (in degrees Celsius). The average peak snow mass date for the data set is Julian day 75.4, and is given by the dashed black line.

results are consistent with the modeling component of our study. To model the changing snowpack, we carried out a climate simulation with a 36-km regional atmospheric model covering all of California. In this simulation, the model is forced at its lateral boundaries with output from a global model simulating future climate change. This allows us to examine the effect of increasing greenhouse gases on the Sierra snowpack. By the mid-21st century, we project significant decreases in snow water equivalent averaged over the wet season in the Sierra Nevada. The projected snow decrease is especially large in the lower-elevation northern Sierras. Here it is about 30-40% in fall and almost 60-80% in winter. The decrease in snow is due to a significant decrease in snowfall and is likely augmented by increased likelihood of melting due to warming. While the likelihood of snow melting is greater in the warmer climate, thus reducing snowpack, the amount of snowmelt itself decreases throughout the cold season in response to the reduced snowfall. Again, the largest reduction occurs in the northern Sierra Nevada where the snowmelt decreases by 38% and 54% for fall and winter, respectively.

A theme emerges from our observational study showing recent earlier snowmelt in response to warmer temperatures and our modeling study showing reduced snowpack in future decades due to warmer temperatures. Together, they indicate the snowpack will likely undergo dramatic changes in the coming decades and moreover, that those changes are already detectable and well underway. These results are directly relevant for California's reservoir infrastructure, whose capacity was designed assuming continuation of the natural hydrologic reservoir of the Sierra snowpack. Clearly this is not the case.

Professional Presentations

Waliser, Duane, Mimi Hughes, and Sarah Kapnick, Anthropogenic Climate Changes in California: Hydroclimate, Snowpack, and Santa Ana Winds, California Climate Change Conference, Sacramento, CA, September 2008.

Kapnick, Sarah, Observed Climate-Snowpack Relationships in California and Their Implications for the Future (poster), California Climate Change Conference, Sacramento, CA, September 2008.

Collaborative Efforts

This effort is also supported through a partnership with the UCLA Joint Institute for Regional Earth System Science and Engineering (JIFRESSE). JIFRESSE supported the implementation and running of the atmospheric model to simulate climate change in California.

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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 altering flood regimes and streamflow patterns. This goal of the current study is to provide improved understanding of the impacts of expanding urbanization on hydrologic response and regional water supply and provide relevant information for decision-makers on alternative land-cover patterns.

Urbanization has been shown to impact surface water and groundwater quality and quantity. Many of the studies addressing urbanization and the related impacts on water resources are undertaken in humid regions. This research is undertaken to improve our 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 flow dynamics in a rapidly urbanizing watershed 2) Can the EPA's HSPF model adequately simulate current hydrologic behavior in semi-arid watersheds? 3) Can the calibrated basin-scale model predict the impacts of proposed expansion in development and provide reasonable assessment of future hydrologic changes? 4) And finally, what is the potential loss of recharge and water supply given increasing urbanization in southern California watersheds?

The upper portion of the Santa Clara River (SCR) is the primary study area. The 640 mi^2 watershed, located 30 miles north of the city of Los Angeles, is in 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. The semi-arid 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 utilized 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.

Results indicate that optimal performance of the HSPF includes distributed precipitation forcing and parameters (semi-distributed model). The model also shows slightly better performance during wetter seasons and years than during drier periods. Potential urbanization scenarios (four distinct levels of expansion) were generated on the basis of a regional development plan. The

validated basin-scale model was run under the proposed development scenarios for a ten year period. Results reveal that increasing development increases total annual runoff and wet season flows, while decreases are observed in baseflow and groundwater recharge during both dry and wet seasons. As development increases, medium sized storms increase in both peak flow and overall volume, while low and high flow events (extremes) appear less affected. Urbanization (over a 217 km^2 sub-basin) is shown to decrease recharge, ranging from 0.145 Mm^3/yr for the lowest development plan to 0.859 Mm^3/r for the largest development scenario. When considered at the regional scale, the predicted decrease in recharge results in a significant loss of potential water supply to southern California.

Professional Presentations

Hogue, T.S., Toward Improved Understanding of Hydrologic Response in Altered Landscapes, Invited Talk - Atmospheric and Geologic Sciences Seminar Series, Iowa State University, Ames, IA, Sept. 2007.

He, M., and T.S. Hogue, Predictive Modeling of Urbanization Impacts on Flow Regimes in a Semi-arid Watershed in Southern California, AGU Fall National Meeting, San Francisco, CA, Dec. 2007.

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

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This study examined spatial relationships between large wood (LW), salmon redds, and habitat units at multiple spatial scales along a 7.7 km reach, using GIS as a primary data interpretation tool. Findings substantiate the view that LW, even at low densities such as those on a regulated river, is an integral habitat heterogeneity component necessary for riverine geomorphic and ecological health. This study contributes to increasing evidence that LW is sought out by spawners when habitat conditions are not optimal.

Few river rehabilitation projects have considered large wood (LW) as a tool for improving salmon spawning habitat, and there is little science to guide the enhancement or placement of LW in that context. This research investigated the role of LW on a regulated river in the Mediterranean climate zone of California, in order to develop a scientific conceptual model of LW dynamics and a decision-making framework that will enable river managers to include LW structures in rehabilitation designs.

(1) To obtain insight into LW dynamics at the reach, geomorphic, and hydraulic scales in regulated rivers, large wood (>1 m length, >10 cm diameter) data was collected from the 7.7 km reach below Camanche Dam fish fence to Mackville Road Bridge on the Mokelumne River, CA, between September 2006 and March 2007. A GIS database of all LW structures, hydraulic habitat units, geomorphic channel characteristics, and redd locations for the 2006-2007 field season was produced using ESRI ArcGIS 9.2.

Key findings: at the reach scale, 85% of redds were within one average channel width (31 m) of LW. At the geomorphic scale (~10^0-10^1 average channel widths), redds were clustered on habitat rehabilitation sites in optimal habitat, and near LW and islands in marginal habitat. At the hydraulic scale (~10^{-1}-10^0 average channel widths) LW was significantly associated with redds in marginal habitat at 10 m, 5 m, and 2.5 m scales.

(2) To study LW placements, a logjam consisting of 30 logs with lengths > 5 m and diameters > 30 cm was built on the Mokelumne River 500 m downstream of Camanche Dam fish fence in September 2007. Another 20 LW pieces were added to the structure in August 2008. 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.

Key findings: Monitoring by East Bay Municipal Utilities District (EBMUD) biologists revealed that the logjam provided new habitat for juvenile salmon in the upper 500 m of the river in spring of 2008. This was the first time juveniles were found in this reach – most move downstream immediately. The additional logs added in summer '08 and continued monitoring may reveal a larger pattern of aquatic organism use of the jam.

(3) To develop a model of LW dynamics above reservoirs, fieldwork was conducted in summer 2006 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. LW originated in the upper watershed and transported into the reservoirs during high precipitation and snowmelt

events in water year 2005-06. A helium-filled blimp with attached camera was used to obtain aerial photographs in order to quantify the wood. Historical records on wood quantities entering reservoirs have been difficult to obtain, as official documents are generally not kept. Library research at the UC Berkeley Water Resources Center Archives photo archives in winter 2007-08 yielded ~20 potential aerial photographs that will help quantify historical wood loads in Sierran reservoirs.

Future research: A PhD proposal is in development that expects to formulate and test a model that predicts wood flux into reservoirs based on wood recruitment potential, flow rates into reservoirs, forest condition, and significant upper watershed precipitation events (rainfall intensity, duration, and frequency, and snowmelt runoff intensity and duration). The model will assist below-dam river managers and restoration practitioners in the determination of suitable LW quantities to include in rehabilitation projects designed to enhance salmon spawning habitat.

Professional Presentations

Senter, Anne E. and Gregory B. Pasternack, Using Large Wood as a River Rehabilitation Tool: Engineered Log Jam (ELJ) on the Mokelumne River. UC Davis Extension Spawning Habitat Rehabilitation class, November 2007.

Senter, Anne E. and Gregory B. Pasternack, Geomorphic and Ecologic Interactions of Large Wood, Pacific Salmonid Redds, and Hydraulic Habitat Units on a Regulated California River, American Geophysical Union, San Francisco, CA, December 2007.

Senter, Anne E. and Gregory B. Pasternack, Geomorphic and Ecological Interactions of Large Wood and Pacific Salmonid Redds across Habitat Units, Mokelumne River, Salmon Restoration Federation Conference, Lodi, CA, March 2008.

Senter, Anne E., Large Wood and Chinook Salmon Redd Interactions on a Regulated River in California, Master's Thesis Defense at UC Davis Hydrology Graduate Group Seminar Series, May 2008.

Senter, Anne E. and Gregory B. Pasternack, Large Wood Aids Chinook Salmon (*Oncorhynchus tshawytscha*) Spawning on a Regulated River in Central California, CALFED Conference, October 2008.

Collaborative Efforts

PI Greg Pasternack has collaborated with East Bay Municipal Utilities District (EB MUD) extensively since 1999 on rehabilitation projects on the Mokelumne River below Camanche Dam. The LWM project funded by this grant received additional funding through an EBMUD-affiliated grant.

Dr. Joseph Merz, an EBMUD fisheries biologist who has been extensively involved in the rehabilitation projects, was 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. Dr. Herve' Piegay has agreed to be a member of Anne Senter's dissertation committee.

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

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In the first two years of our project, our work in Owens Valley showed that both soil nitrogen and groundwater availability were important determinants of plant and community processes. This year, we developed a conceptual framework for the linkages between water availability, plant responses to water stress, plant chemical composition, and soil nutrient cycling. We propose that plant water stress and nutrient cycling are linked by the relationship between plant chemical composition and vulnerability to cavitation, a measurement of the ability of plants to withstand water stress. Our measurements support this hypothesis, which may provide important new insights in ecohydrology and the responses of ecosystems to hydrologic change.

Owens Valley, California has been an important source of water for the city of Los Angeles for nearly one hundred years. Since 1913, the valley's groundwater has been pumped and diverted to Los Angeles for the city's water supply. However, it is difficult to predict the consequences of water redistribution for ecosystem and soil processes as the linkages between ecology and hydrology are relatively poorly understood.

While previous studies have evaluated water availability as the primary driver of vegetation change in Owens Valley, our work to date has demonstrated that nitrogen availability is also a primary driver of plant processes, and in some cases may be more important than groundwater depth in influencing ecosystem function (Pataki et al. 2008, Goedhart et al. In review). In the final year of this project, we have developed a conceptual framework that links water availability and nutrient relations to improve our understanding of ecohydrology.

A major physiological response of plants to water stress is cavitation, or introduction of air embolisms, into xylem. Embolisms block the flow of water and prevent water uptake, potentially leading to catastrophic failure of the vascular system. Plants with greater resistance to cavitation have been shown to have greater xylem density and strength, indicating that xylem of resistant species contains different proportions of material than xylem of less resistant species. Because plant chemical composition is closely related to rates of decomposition and ecosystem nutrient cycling, there are important implications of variations in vulnerability to cavitation for biogeochemistry that have not yet been explored. Lignin is a strengthening compound that is found predominantly in the secondary cell wall of vessel elements and fibers, and is likely to be closely associated with plant resistance to cavitation. Lignin is quite resistant to degradation, and plant material composed of a greater proportion of lignin may inhibit decomposition of plant litter and woody debris. If vulnerability to cavitation is correlated with stem and root lignification, changes in ecosystem water availability may change the amount of lignin delivered to soils – either by increased lignification of xylem in existing plant populations, or by shifts in community composition toward more water stress resistant species.

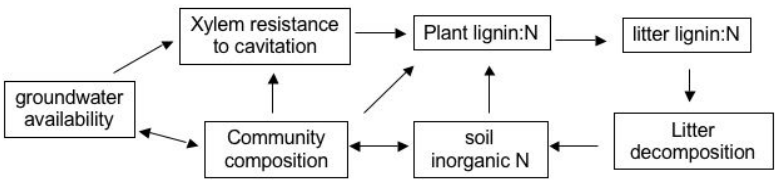

Figure 1.

Our conceptual framework for the linkages among these processes is shown in Figure 1. We have measured plant vulnerability to cavitation, chemical composition, and soil nutrient availability across a depth to groundwater gradient in Owens Valley to test some of these linkages. We found increasing water stress in the shrub species *Ericameria nauseosa* with increasing water table depth, using leaf carbon isotopes ($\delta^{13}C$) as a measure of water stress. The percent lignin in the stem of this species also increased with watertable depth, consistent with our hypothesis. In fact, $\delta^{13}C$ and percent lignin were significantly correlated.

Vulnerability to cavitation, expressed as xylem pressure at 75% loss of hydraulic conductance, decreased across the water-table gradient. Xylem pressure and stem lignin content were also significantly correlated. This is very consistent with our conceptual model in Figure 1. As watertable depth increased, plants developed great resistance to water stress, which resulted in stronger, more lignified xylem. This is an important relationship between plant water stress adaptation and chemical composition that has not been previously described.

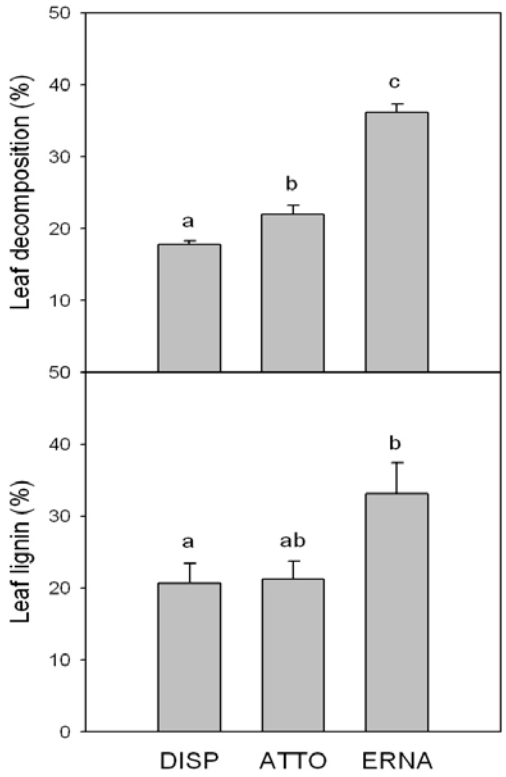

Figure 2.

We also conducted a litter decomposition study in which litter bags containing leaf litter from dominant species were placed at sites of varying grass and shrub cover during the wet season. The results were actually the reverse of what we originally predicted: *Ericameria nauseosa* had the highest lignin content but also showed the most rapid rates of decomposition in situ (Figure 2). This is likely due to photo-degradation of litter, which is commonly observed in surface litter in arid ecosystems. Therefore, a key next step in this research is to study decomposition rates in buried litter bags and in litter containing root material rather than leaf material, to further elucidate the relationships in Figure 1.

Our results show that in order to understand the linkages between hydrologic and vegetation change, predictive models need to incorporate higher order feedbacks between water stress, nutrient cycling, and plant adaptations to water and nutrient limitations.

Publications

Pataki, D.E., Billings, S.A., Naumburg, E., Goedhart, C.M. 2008. Water sources and nitrogen relations of grasses and shrubs in phreatophytic communities of the Great Basin Desert. Journal of Arid Environments 72(9): 1581-1593.

Collaborative Efforts

The Los Angeles Dept. of Water and Power helped us select our study sites and gave us permission to conduct this research on their property.

Professional Presentations

Goedhart, C.M., Pataki, D.E. Are plant adaptations to water stress and the chemical content of organic matter directly linked?" Ecological Society of America meeting, Milwaukee, WI, August 2008.

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High Resolution Modeling of Flood Inundation

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This project aims to advance the state of the art in urban flood modeling by tailoring multi-dimensional flood inundation models to increasingly available high-resolution geospatial data-sets including LiDAR DEMs, aerial imagery and other datasets of urban landscape features.

Government at all levels is increasingly investing in Geographical Information Systems (GIS) to archive, access, and regularly utilize a wide range of important data resources. These data are particularly rich in urban areas due to the density of infrastructure. Data sets characterize a vast array of features including parcel boundaries and building footprints, land cover attributes, critical lifeline infrastructure and census data. Flood risk management efforts increasingly rely on economic, social and environmental factors to measure the consequences of flooding. By combining data archived in government GIS with flood inundation predictions, it becomes possible to make highly resolved damage assessments required for decision making. However, flood inundation modeling technology has not kept pace with recent changes in data resources, and many of today's models are not well suited to the challenge of routing flow through urban areas, nor the diverse flooding threats that stem from infrastructure failures such as levee breaks. Our research aims to advance a new generation of high-resolution, multi-dimensional flood inundation models that leverage data resources and build upon fundamental advances made in the computational sciences over the past decade. In particular, we are interested in modeling urban flood inundation.

In urban areas, there is a high degree of spatial variability in land surface properties resulting from built structures and variable land covers (concrete, vegetated strips, buildings). In this project, we have focused on effective strategies to incorporate the effects of these attributes on flood hydrodynamics by leveraging increasingly accessible geospatial datasets such as Light Detection and Ranging (LiDAR) terrain height surveys, aerial imagery, and vector datasets such as building footprint polygons, as shown in Fig.1.

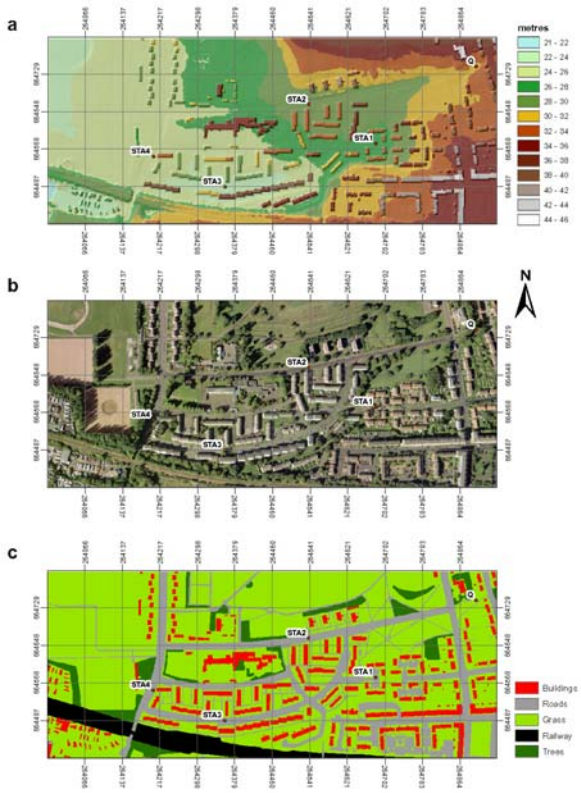

Fig. 1. (a) LiDAR terrain data, (b) aerial imagery and (c) building footprint data used in flood inundation modeling at Glasgow site

Fig. 2. Model prediction of flood extent.

Our research has identified a novel method to generate unstructured computational meshes that are constrained by critical landscape features such as building walls and levees, and to estimate resistance parameters from aerial imagery and landcover data. This improves the accuracy and efficiency of urban flood predictions such as shown in Fig. 2. However, modelers must evaluate whether improved run-time performance outweighs a longer model set-up procedure.

Model efficiency is a central theme of our research. A fine resolution mesh (~1 m) may be needed to resolve detailed land surface features which impact flood propagation, but this can be computationally cost prohibitive for river basin scale flood inundation modeling. To address this problem, we have researched use of a flood plain "porosity" to account building effects on a relatively coarse grid, say 10 m resolution. Both volumetric porosity and areal porosity have been derived to account for storage and conveyance effects, respectively. Areal porosity is directionally dependent which introduces anisotropy to the shallow-water equations and captures sub-grid preferential flow directions which occur in urban settings. Fig. 3 shows a prediction of depth and velocity around an array of blocks representative of buildings in a flood plain. This shows that the porous equations give a very similar prediction compared to the classical equations, but require less than 1% of the computational effort!

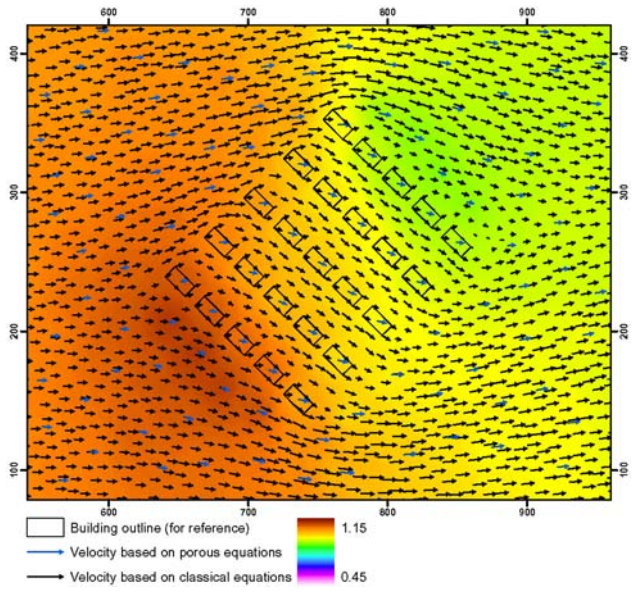

Fig. 3. Flood depth and velocity predicted by porous and classical shallow-water equations.

Publications

Schubert, J.E., Sanders, B.F., Smith, M.J. and Wright, N.G. Unstructured mesh generation and landcover-based resistance for hydrodynamic modeling of urban flooding, *Advances in Water Resources*, 31, 1603-1621, 2008.

Sanders, B.F., Schubert, J.E. and Gallegos, H.A. Integral formulation of shallow-water equations with anisotropic porosity for urban flood modeling, *Journal of Hydrology*, 362, 19-38, 2008.

Professional Presentations

Sanders, B.F. Advances in flood inundation modeling and integration of GIS, Los Angeles County, Department of Regional Planning, August 15, 2007.

Sanders, B.F. Advances and opportunities in flood inundation modeling using high resolution geospatial data, Los Angeles County Department of Public Works, September 18, 2007.

Sanders, B.F. Advances in flood inundation and the role of GIS, City of Los Angeles, Dept. of Public Works, Bureau of Engineering GIS Meeting, September 4, 2008.

Collaborative Efforts

I have collaborated on this research with colleagues in the United Kingdom who participate in the UK Flood Risk Management Research Consortium, as well as researchers in the Netherlands associated with the UNESCO-IHE Institute for Water Education.

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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.

Reconstruction of Sierra Nevada Hydrology over the Last Millennium

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It is crucial that we understand the hydrologic response of the Sierra Nevada Mountains—a primary source of fresh water for Southern California—to projected climate change over the next few decades to centuries. This study aims to contribute to this understanding by reconstructing hydrologic conditions of the Sierra Nevada over the last millennium

Climate change and growing demand for fresh water in Southern California over the 21st century leaves the region highly vulnerable to severe drought and the resulting environmental damage and socioeconomic disruption. For example, much of Southern California's freshwater supply relies on the accumulation snow pack and the release of snowmelt from the Sierra Nevada Mountains, processes which may already be impacted by the effects of a warming climate. Furthermore, studies of past climate indicate that at certain periods over the last millennium, the entire western United States was witness to droughts of greater duration and severity than any in recorded history. It is therefore crucial that we understand the hydrologic response of the Sierra Nevada Mountains to projected climate change over the next few decades to centuries. This study aims to contribute to this understanding by reconstructing hydrologic conditions of these mountains over the last millennium through the collection and analysis of a suite of sediment cores from Swamp Lake, located in an isolated catchment at the northwest corner of Yosemite National Park.

We established two primary goals in carrying out this project: 1) create a time series of hydrologic variability in the western Sierra Nevada through analysis of Swamp Lake sediment morphology and geochemistry and, 2) determine the quality with which climate information is recorded in the sedimentary archive through a comparison of the uppermost sedimentary layers with the instrumental record of the last several decades. Below we describe our ongoing analyses of the Swamp Lake cores and the progress made towards accomplishing these goals.

Having collected the sediment cores during field expeditions in 2006 and 2007, we have focused our efforts thus far on analyzing properties of the most recent sediment, that which was deposited within the period of instrumental record. By comparing results with instrumental observations, we can assess the ability of these analyses to reveal information about Sierra Nevada hydrology over the past millennium. High-resolution images of core surfaces were complied at the Limnological Research Center (LRC) at the University of Minnesota, Minneapolis and analyzed to create a time series of varve thickness and light/dark (grey scale) intensity. Through further investigation of these images and comparison of results with existing hydrologic reconstructions from across the western United States we will attempt to determine the relationship between the thickness of seasonal varve components and sediment grey scale values to the hydrology of the area.

A record of hydrogen isotope ratios (δD) from a specific organic compound, probably from terrestrial and aquatic plants around the perimeter of the lake, was extracted from the recent five decades sampled from the upper core sediments in order to compare δD with known variability from the instrumental climate record. Comparison of

Researchers collecting a frozen sediment core from Swamp Lake, September 2006.

the preliminary δD series with that of total annual precipitation from the Yosemite region reveals a significant, though somewhat weak correlation. Results also indicate that the δD variations may reflect the amount of precipitation that is deposited as snow vs. rain. The partitioning between snow and rain is of particular interest because winter-deposited snow pack has the capacity to store fresh water that later becomes available in the spring and summer months while rain quickly runs off the mountains and in extreme cases can overwhelm rivers and reservoir infrastructure. Analyses are continuing to clarify these linkages, and then to use these relationships, along with longer, downcore series of δD, to reconstruct precipitation and its snow/rain components during past centuries. This work should provide a longer hydrologic record of wet and dry and warmer and cooler episodes in the region.

The results of this study will help construct a climatologic framework within which the Sierra Nevada Mountains, the major source of California's water supply, has operated over the last millennium. This framework can then be projected onto the coming decades in order to anticipate how California's hydrology may vary in the future and to provide insight into how it will respond to climate change. Such information is crucial in the face of an already warming climate and continually growing demand.

Professional Presentations

Roach, Lydia, Daniel Cayan and Christopher Charles, Modern Swamp Lake Cores: A Potential Tracer for Decadal Scale Hydroclimate Variability Over the Last Millennium, Yosemite Hydroclimate Workshop, Yosemite National Park, CA, October 2008.

Collaborative Efforts

Field work in Yosemite National Park was permitted by the National Park Service. Logistical support was provided by Jan Van Wagtendonk of the US Geological Survey and by Jim Roach and Josh Bacchi and Sam Seimens of Yosemite National Park. We received considerable support, including coring and raft equipment and from Scott Anderson of Northern Arizona University, who was familiar with Swamp Lake from earlier coring expeditions. Jane Teranes of the UCSD Environmental Science Program assisted with lake coring operations in 2006. Core Processing facilities and storage was provided at the University of Minnesota Limnological Research Center (LRC) Core Facility. The 2007 Swamp Lake coring team included LRC technician Kristina Brady, who supplied coring equipment and guided coring operations using the Bolivia corer. Hydrogen isotope analysis is carried out in direct collaboration with Alex Sessions at the California Institute of Technology with all sample processing and δD measurements made in his lab. We intend to collaborate with Thomas Guilderson at the Lawrence Livermore National Laboratory in obtaining radiocarbon dates and establishing a robust chronology for the Swamp Lake cores.

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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, while denitrification rates are low or undetected during the conditions in which we sampled.

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

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 were low or undetected in nearly all sites under the conditions we sampled (intertidal mudflats at low tide).

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. Denitrification increased dramatically in response to increased nitrate concentrations, though it appears that this increase is not enough to remove large quantities of excess nitrogen these systems may experience.

In July – August 2005 we performed a sediment transplant experiment to investigate how microbial nitrogen processing rates are affected by differences in sediment types.

Denitrification was undetected in these sediments, perhaps due to sampling technique.

In June – July 2006, a 40-day field experiment investigated how the presence and density of green macroalgal mats affect nitrogen fixation and denitrification rates and other sediment and water characteristics beneath the algal mats. Denitrification rates showed no activity and require further investigation.

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. These processes that add and remove nitrogen from estuarine ecosystems are especially important as nutrient loading and subsequent eutrophication will only increase in the future.

During the past year, we have been able to complete the processing of all samples we collected and are in the process of analyzing all data and writing papers for publication. We have also started an additional related project to investigate denitrification in other southern California estuarine systems using additional methods that are expected to complement the results of this research.

Professional Presentations

Kane, T. and P. Fong. Nitrogen fixation and denitrification in a eutrophic southern California estuary: rates and responses to abiotic characteristics. California Estuarine Research Society Meeting, Ensenada, Baja, Mexico, March 2008.

Kane, T. and P. Fong. Quantifying sediment nitrogen fixation and denitrification rates and responses to abiotic characteristics of a eutrophic southern California estuary. American Society of Limnology & Oceanography, Ocean Sciences Meeting, Orlando, FL, February 2008.

Kane, Tonya and Peggy Fong. Sediment nitrogen fixation in Upper Newport Bay Estuary, southern California. Department of Ecology and Evolutionary Biology 10th Annual Research Symposium. Los Angeles, CA, May 2007.

Collaborative Efforts

Determination of nitrogen fixation and denitrification rates requires a Gas Chromatograph (GC) in order to measure gas concentrations obtained during assays. Dr. Doug Capone at the University of Southern California has allowed us to use his GC for nitrogen fixation measurements. He and members of his laboratory have also been very helpful in teaching us the techniques required to measure these characteristics. Larry Miller and John Duff at USGS, Menlo Park, have provided us with time in their labs to run all of our denitrification samples. Without their collaboration we would not have been able to carry out this research.

This work also fostered collaboration with the Southern California Coastal Water Research Project (SCCWRP), and led to a multiple researcher and multiple stakeholder collaboration project 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 investigate these processes in five San Diego estuaries and lagoons. This research is currently being performed and will greatly expand knowledge and understanding of microbial nutrient processes affecting southern California's highly impacted estuarine habitats. Results of this research will be used by managers to determine Total Maximum Daily Load (TMDL) regulations of nutrients to these systems.

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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.

Both scientists and the public recognize the importance of wetlands. 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. Searches of the scientific literature indicate a lack of research on the biogeochemical and hydrological cycles of California Tule Marshes. The disconnect is obvious: scientists and the public recognize wetlands as critically important, but understanding of the ecological processes that control the functioning of California wetlands is lacking.

We are working at UCI's San Joaquin Freshwater Marsh (SJFM) to better understand the ecological controls on wetland carbon, energy and water vapor exchange. The SJFM is an 82-ha *Typha latifolia* and *Scirpus californicus* remnant of a large historical wetland. The marsh is located on the UCI campus, allowing easy access and facilitating undergraduate and graduate student training. The main goal of our UCWRC-funded research is to understand the biophysical and environmental controls on carbon, energy, and water vapor exchanges at the SJFM.

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 1999-2008 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). 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 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 that is characterized by a large accumulation of litter. We hypothesize 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 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. 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

Rocha, A.V. (2008) The importance of intrinsic controls in driving interannual NEP variability. Ph.D. Dissertation. UC Irvine. Department of Earth Systems Science.

Rocha, A.V., D.L. Potts, and M.L. Goulden (2008), Standing litter as a driver of interannual CO2 exchange variability in a freshwater marsh, JGR-Biogeosciences, In Press.

Rocha, A.V., and M.L. Goulden (2008), Why is marsh productivity so high? New insights from eddy covariance and biomass measurements in a Typha marsh, Agricultural and Forest Meteorology, In Press.

Rocha, A.V., and M.L. Goulden (2008), Large interannual CO2 and energy exchange variability in a freshwater marsh under consistent environmental conditions, JGR Biogeosciences, In Press.

Goulden, M.L., M.C. Litvak, and S.D. Miller (2007), Factors controlling marsh evapotranspiration, Aquatic Botany, 58, 97-106.

Professional Presentations

Adrian V Rocha and Michael 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.

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, such as the Quagga mussel) 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, collecting information regarding lakes visited before and after present use, travel within Lake Tahoe, invasive species awareness, boat cleaning habits, and vessel inspections for vegetation caught on boats

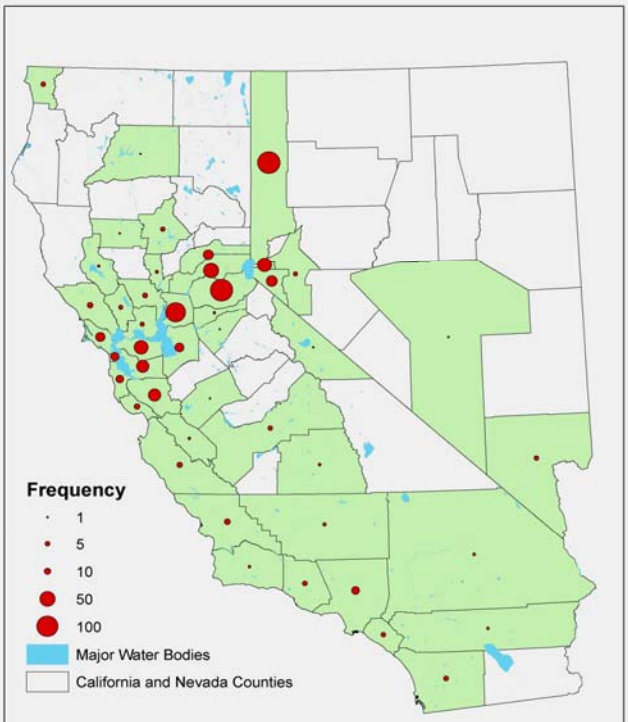

Figure 1. County originations for Tahoe boaters

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 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 originate from a large geographic range (Figure 1), and have previous use in water bodies with known aquatic invaders, including Western reservoirs known to have established populations of Quagga mussel; 15% of boats leaving Lake Tahoe carry invasive plant species fragments on equipment; some habitats within Lake Tahoe may limit the establishment and growth of Eurasian watermilfoil because of wave action and sediment quality, other habitats in the lake are appropriate for Eurasian watermilfoil growth – suggesting that the invasion is still in progress; Eurasian watermilfoil and Curlyleaf pondweed continue to spread in Lake Tahoe; a majority of Lake Tahoe boaters *never* conduct visual inspection of boats or boating equipment for ANS; a number of California and Nevada lakes contain ANS that have not been previously reported.

Professional Presentations

Wittmann, Marion, E., Pathways for Aquatic Invasive Species, Western Aquatic Plant Man. Society, Lake Tahoe CA, March 2008.

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. University of Nevada, Reno researchers provided field assistance.

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Control of Mercury Methylation in Wetlands through Iron Addition

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In order to improve aquatic habitat in the San Francisco Bay and other critical habitats, 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 addition of iron to wetland sediments as a potential landscape-scale approach to decreasing methylmercury production.

Methylmercury (MeHg) is a potent neurotoxin that can be detrimental to 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 tidal salt marsh around South 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 investigating a potential method of reducing net mercury methylation rates through the addition of ferrous iron to wetland sediments. After iron addition, the concentration of dissolved sulfide decreases through the formation of $FeS_{(s)}$. Sulfate-reducing bacteria also produce less MeHg because the concentration of dissolved, bioavailable mercury decreases as sulfide concentrations decrease. In a previous research project, we showed that iron addition decreases net MeHg production in pure cultures of sulfate-reducing bacteria and in wetland sediment slurry systems. We are now investigating the efficacy of iron addition under conditions that more closely approximate those encountered in wetlands by using laboratory microcosms collected from a tidally influenced estuarine wetland in San Francisco Bay.

David Sedlak and Patrick Ulrich collect wetland microcosm cores from a tidal salt marsh along the Petaluma River.

In early Fall 2007, twelve intact sediment cores were collected into acrylic microcosms from a salt marsh located along the Petaluma River in Sonoma County. These microcosms were brought back into the lab, where they were kept under a simulated light and tidal cycle operated by automated grow lamps and peristaltic pumps. The microcosms were allowed to equilibrate to the laboratory conditions for a few months before experimental manipulations began. At the start of the experiment, the microcosms were randomly divided into four iron dosing groups, corresponding to a control with no iron addition, and low, medium, and high iron dose groups receiving additions of 180, 360, and 720 g-Fe/m^2, respectively. Over the course of a 3-month period, we found that dissolved sulfide concentrations decreased for all three iron addition levels relative to the control, without significantly altering microbial sulfate reduction rates. The medium and high iron dose groups also contained lower concentrations of total mercury and methylmercury, with methylmercury concentrations declining by as much as 94%.

Experimental setup for laboratory wetland microcosm operation.

This experiment further demonstrated that the addition of ferrous iron to tidal wetland sediments has the potential to be a practical landscape-scale control that could be implemented during wetland construction and restoration projects throughout California. Additional research is planned to further evaluate the efficacy of an iron amendment in the presence of wetland vegetation, as well as under actual field conditions.

Professional Presentations

Sedlak, David and Patrick Ulrich, Can we use iron to control methylation rates in wetlands? Delta Tributaries Mercury Council Quarterly Meeting, Sacramento, CA, May 2008.

Sedlak, David and Patrick Ulrich, Use of iron to control mercury methylation in wetland sediments, International Conference on Research Frontiers in Chalcogen Cycle Science and Technology, Wageningen, Holland, May 2008.

Ulrich, Patrick and David Sedlak, Decrease in net mercury methylation following an iron amendment to wetland microcosms, Gordon Research Conference on Environmental Bioinorganic Chemistry, Waterville Valley, NH, June 2008.

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 and Fisheries: Pine Creek Watershed and Eagle Lake Rainbow Trout

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This is the second 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.

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 spring 2008 we used passive integrated transponder (PIT) antennas to track the upstream movement of ELRT spawners. We captured a sample of ELRT at the barrier near the mouth of Pine Creek during the spring spawning migration period. The fish were anesthetized and surgically implanted with PIT tags. After a recovery period, fish were released upstream of the passage barrier. Upstream migration of ELRT was monitored in the lower, middle, and upper sections of Pine Creek with five channel-spanning stationary PIT antennas. Pine Creek naturally flows all the way from its headwaters to Eagle Lake only during the spring snowmelt period. In summer, only the upper 6 miles of the creek has water, so spawners must reach this area in order for their offspring to rear successfully. Stream flow was low and erratic in 2008, and ELRT migrated less than 2 miles upstream, far short of the 22 miles necessary to reach areas with perennial summer flows.

In order to relate ELRT migration to environmental factors and potential impacts of climate change, we assembled historical data for stream flow, snowpack, air temperature, and fish migration distances (the furthest distance an ELRT swam up Pine Creek in a given year). Migration distance was positively related to seasonal average stream flow, total days of flow, and April snowpack. April air temperature did not help in interpreting the effect of snowpack and melting patterns. However, only monthly average temperature data were available. In the future, more detailed temperature data that show heat

wave patterns may be useful.

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. We are testing methods to decrease the competition and predation that juvenile ELRT face from brook trout. In August 2007, we electrofished all of Bogard Spring Creek, a small tributary of Pine Creek, to assess ELRT and brook trout abundance, and removed all the brook trout that we captured. We also sampled parts of Pine Creek, but left the brook trout in the creek as a control area. In September 2008 we repeated the electrofishing sampling in both creeks to assess the effect of removing brook trout on the abundance and growth of ELRT. Numbers of brook trout were 69% lower in Bogard Spring Creek in 2008, while brook trout numbers in Pine Creek were similar to the previous year, suggesting that the removal did in fact suppress brook trout. However, numbers of other species, such as rainbow trout, Tahoe sucker, and speckled dace, were also lower in Bogard Spring Creek in 2008. This suggests that factors other than the brook trout removal, such as a dry year in 2008, have affected fish.

Creek	Fish species	Numbers of Fish		% change
		2007	2008	
Bogard	Brook trout	4886	1525	-69
	Rainbow trout	170	25	-85
	Tahoe sucker	73	31	-58
	Speckled dace	150	38	-75
Pine	Brook trout	653	603	-8

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

Publications

Thompson, Lisa C., Gerard Carmona Catot, Teresa Pustejovsky, and David Lile. 2007. Pine Creek and Eagle Lake Rainbow Trout Study – 2007: Spawner Migration, Upper Watershed Habitat and Rearing Survey, and Bogard Spring Creek Brook Trout Removal Experiment. Report to the Pine Creek Coordinated Resource Management Planning Group. 30 November 2007. Lassen County Publication. 22 p.

Selected 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.

Thompson, Lisa, Gerard Carmona Catot, Teresa Pustejovsky, and David Lile. Restoring Pine Creek Watershed & Eagle Lake Rainbow Trout: Presentation of 2007 results of Eagle Lake Rainbow Trout Study. Pine Creek Coordinated Resources Management Planning Group (CRMP) meeting. Susanville, CA. November 30, 2007.

Thompson, Lisa C., David F. Lile, Peter B. Moyle, Kenneth W. Tate, Teresa E. Pustejovsky, Gerard Carmona Catot, Karen Vandersall, & Craig Fergus. Restoring a rangeland watershed & its endemic rainbow trout: Pine Creek, California. American Fisheries Society Annual Meeting. Ottawa, Canada. August 18, 2008.

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 in spring, summer, and autumn 2008. US Forest Service staff supplied, installed, and monitored water temperature loggers along the length of Pine Creek.

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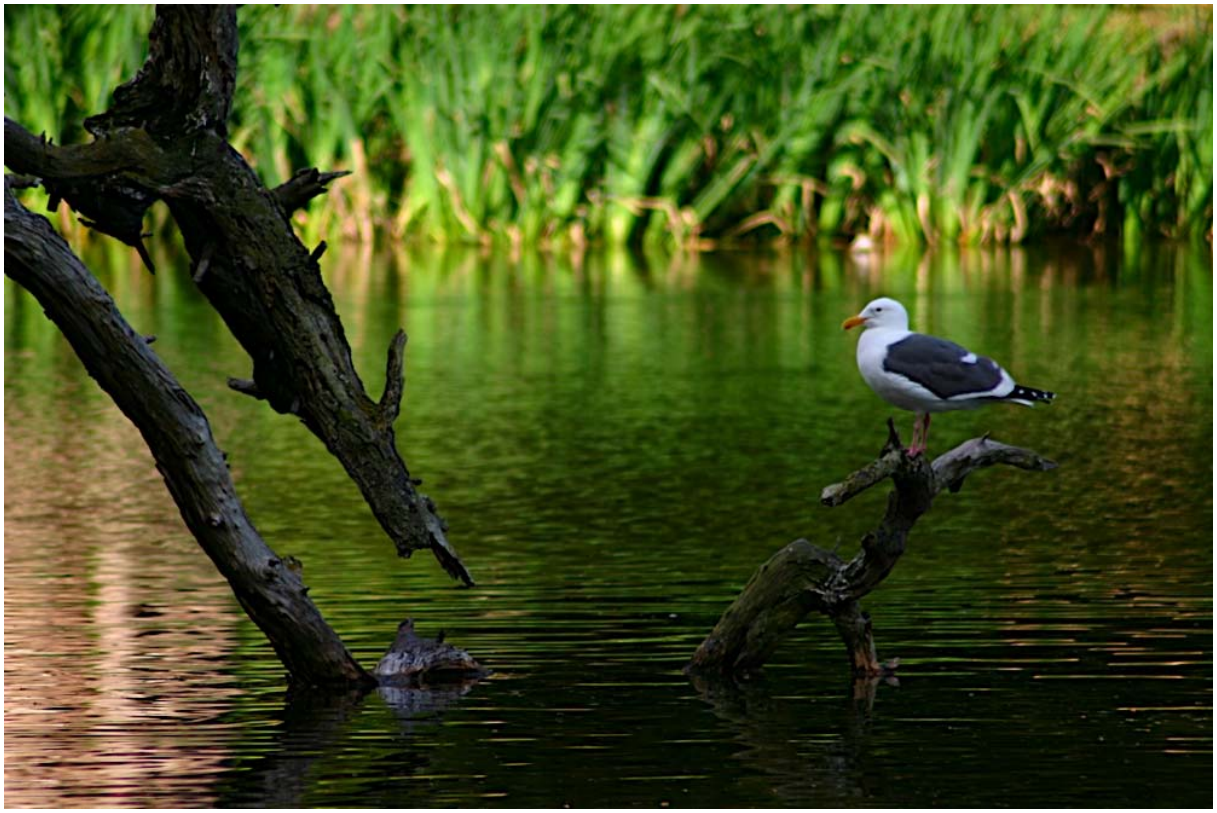
Research Category III

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.



Microbial Degradation of Polybrominated Diphenyl Ethers (PBDEs)

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Aerobic bacteria capable of degrading polychlorinated biphenyls were tested for the ability to degrade PBDEs. Two strains in particular degraded all PBDEs with fewer than six bromines and one completely transformed the original compound releasing stoichiometric quantities of bromide.

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 breast-milk concentrations have raised concern about their use and have led to regulatory bans for some of the compounds in California.

Bacteria play an important role in the fate of compounds in the environment. Anaerobic dehalogenating microorganisms can remove 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. Aerobic bacteria that degrade polychlorinated biphenyls (PCBs) may be able to degrade PBDEs and could potentially remove PBDEs from the environment. As such, the objectives of our project were to 1) determine whether highly-brominated deca and octa-BDE congeners can be debrominated by anaerobic dehalogenating microorganisms; 2) determine the debromination pathway and 3) determine whether aerobic PCB-degrading bacteria are capable of degrading PBDEs.

Since 2007, we have completed the final objective of this research project. Two known PCB-degrading bacteria, *Rhodococcus jostii* RHA1 and *Burkholderia xenovorans* LB400 were tested for their ability to degrade PBDEs with one to six bromines. Additionally, two related strains, the aromatic-degrading *Rhodococcus sp*. RR1 and the ether-degrading *Pseudonocardia dioxanivorans* CB1190 were also tested. Both RHA1 and LB400 were capable of degrading the mono- through penta-BDEs, and LB400 was able to degrade one of the three tested hexa-BDEs over the course of three days. The extent of degradation varied with more than 90% of the mono- and di-BDEs being degraded whereas between 10 and 45% of the penta-BDEs degraded over the same time period. RR1 and CB1190 only minimally transformed the less brominated congeners (Figure 1).

In order to determine whether the PBDEs were being completely broken down or whether some intermediate was being formed, the samples were analyzed for the production of bromide. Current analytical techniques for detecting bromide did not work for our samples, so a collaboration was set up with Dr. Mehmet Coelhan of the Technical University of Munich, Germany, to develop a new bromide measurement technique that could work in the presence of cells.

Bromide was in fact detected in the RHA1 samples at stoichiometric concentrations, indicating that the PBDE molecule is being entirely degraded. The LB400 samples only

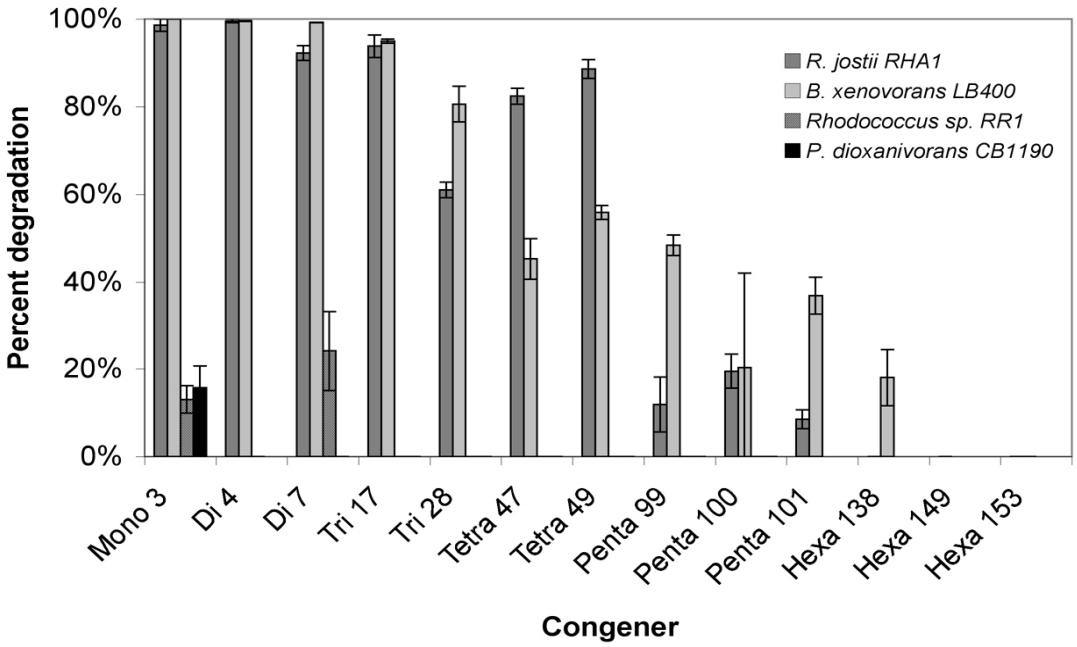

Figure 1. Percent degradation of 13 PBDEs by four aerobic bacteria. Values are averages of triplicates. Error bars represent the standard error.

yielded about 10% of the expected amount of bromide based on the disappearance of the PBDE substrate. GC-MS analysis revealed that the other 90% of the substrate was being transformed to a hydroxylated PBDE. This result is problematic because hydroxylated PBDEs are more endocrine disrupting than the original PBDE.

Publications

Robrock, K.R., P. Korytar, L. Alvarez-Cohen. "Pathways for the Anaerobic Microbial Debromination of Polybrominated Diphenyl Ethers" *Environmental Science & Technology*, 2008, 48 (2) 2845-2852.

Professional Presentations

"Aerobic biodegradation of Polybrominated Diphenyl Ethers (PBDEs) by PCB-degrading bacteria" Invited lecture, Norcal SETAC Conference, Berkeley, CA, May 2008.

Robrock, K., L. Alvarez-Cohen, "Degradation of polybrominated diphenyl ethers by aerobic PCB-degrading organisms." Poster presentation, NIEHS Superfund Basic Research Program Meeting, Duke University, NC, 2007.

Collaborative Efforts

Dr. Mehmet Coelhan at the Technical University of Munich, Germany, helped develop a technique for measuring low concentrations of bromide in the presence of bacterial cells.

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

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This year our goals were to: 1) investigate fecal indicator bacteria (FIB) dynamics in beach sand following sewage spills; 2) use traditional FIB measurements along with a novel rapid FIB method and Bacteroides levels in water and sand to conduct fecal source tracking and identification at three impaired beaches; and 3) continue to collaborate with the Southern California Coastal Water Research Project on an epidemiological study of adverse health impacts due to water and sand exposure.

Coastal sediments are increasingly recognized as important reservoirs of *E. coli* and enterococci, referred to as fecal indicator bacteria (FIB). The abundance of FIB in sediment can have two distinct implications for public health. On one hand, persistence and regrowth of non-pathogenic FIB in sediment weakens the relationship between FIB and the pathogens they are meant to proxy. On the other hand, sediments may provide a favorable environment for pathogens, as they do for FIB, and may be an unexplored route of exposure.

Importantly, both FIB and pathogens appear to have greater persistence in sediments than in water. In general, sediments may be more conducive to FIB survival relative to the water column due to reduced sunlight inactivation, protection from predators, nutrient and organic carbon availability, and the presence of a surface for the formation of biofilms.

Fecal pollution is a major cause of water quality impairment in coastal areas. However, our understanding of the fate of fecal pollution in coastal ecosystems, as well as our ability to identify and mitigate its sources, is greatly limited by uncertainties surrounding its behavior in two major reservoirs: wetlands and beach sediments.

Investigation of FIB dynamics in beach sand following sewage spills.

Factors affecting FIB and pathogen survival/persistence in sand remain largely unstudied. This work elucidates how biological and physical factors affect die-off in beach sand following sewage spills.

Solar disinfection with mechanical mixing was pilot-tested as a disinfection procedure after a large sewage spill in the Los Angeles area. Effects of solar exposure, mechanical mixing, predation and/or competition, season, and moisture were tested at bench scale. Desiccation was a dominant factor for *E. coli* but not enterococci inactivation. Effects of season were investigated through a comparison of experimental results from winter, spring, and fall.

Moisture was the dominant factor controlling *E. coli* inactivation kinetics. Initial microbial community and sand temperature were also important factors. Mechanical mixing, common in beach grooming, did not consistently reduce bacterial levels. Inactivation rates are mainly dependent on moisture and high sand temperature. Chlorination was an effective disinfection treatment.

Use of traditional FIB measurements along with a novel rapid FIB method and Bacteroides levels in water and sand to conduct fecal source tracking and identification at three impaired beaches.

We completed laboratory and field testing of our rapid method for *E. coli* and enterococci based on immunomagnetic separation/ATP quantification (IMS/ATP).

One approach to addressing coastal water quality concerns is the use of source tracking and identification strategies, which have historically been based on FIB as a first tier to direct additional sampling efforts. This tiered approach is hampered by the temporal variability of FIB in aquatic environments. The

tiered approach is further limited by the absence of an economical rapid detection method to serve as a middle tier that would allow investigators to obtain results from multiple samples in near real time and before the contamination source has dissipated.

The development of rapid detection assays, allowing enumeration of microbial contaminants as quickly as one hour and enabling a more diverse suite of organisms to be studied, has progressed significantly in recent years. While many of these assays are promising, only IMS/ATP currently incorporates a feasible on-site analysis that can be optimized to a 30 minute assay of multiple samples.

Until recently, impediments have obstructed the transition and application of IMS/ATP to measurement of water quality in marine systems. We have made significant improvements to the IMS/ATP protocol and its applications; this includes devising a more robust anti-*E.coli* biosorbent, testing the biosorbent in both freshwater and marine waters, and examining IMS/ATP as a rapid and potentially adaptive tier in microbial source tracking and pollution identification.

We devised a covalently-linked anti-*E.coli* bead complex that was used to measure water quality in freshwater and marine systems by IMS/ATP. We collected and analyzed samples from freshwater and marine systems. R^2 values for the correlation between traditional measurements and the rapid method were 0.87 and 0.94 in freshwater and marine, respectively. IMS/ ATP was also evaluated as a rapid, intermediate tier for a multi-tiered approach in source tracking and identification and was able to rapidly identify the presence of high *E. coli* loading in one of the two channels, which resulted in high levels at the confluence of the two channels.

We are currently applying this rapid method along with human-specific and universal Bacteroides measurements by quantitative PCR in two additional watersheds in Malibu and Ventura. We have detected human fecal pollution in the Ventura Marina and are currently continuing source tracking efforts.

Continued collaboration with the Southern California Coastal Water Research Project (SCCWRP) on an epidemiological study of adverse health impacts due to water and sand exposure.

This past summer, we analyzed FIB in sand at Doheny and Avalon beaches as part of the SCCWRP study. We also extracted and purified DNA, and are in the midst of analyzing DNA extracts for human-specific and universal *Bacteroides*. The study is ongoing and results are not yet available.

Selected Professional Presentations

Mika, K., G. Imamura, C. Change, C.M. Lee, J.A. Jay, Dynamics in Sand of Fecal Indicator Bacteria (FIB) and *Salmonella* From Contaminated Water, Runoff, and Sewage in an Urbanized Southern California Shoreline. American Geophysical Union Annual Meeting, San Francisco, CA, December, 2007.

Lee, C.M., W. Kaiser, J.A. Jay. Immunomagnetic separation and ATP quantification (IMS/ATP): Evaluating a method of rapidly detecting pathogen indicators in aquatic environments with respect to identifying hotspots of contamination. Gordon Research Conference. Environmental Sciences: Water, New Hampshire, June 22-26, 2008.

Collaborative Efforts

My lab has continued our very meaningful collaboration with Dr. Sharon Walker (UCR). We have received a second year of funding from UC Marine Council for a project stemming from our Center for Water Resources Grant. This year's UC Marine Council award is also in collaboration with Rich Ambrose (UCLA) and Trish Holden (UCSB). Our lab is also pursuing additional source identification funding in collaboration with Trish Holden, Ali Boehm (Stanford) and the Southern California Coastal Water Research Project (SCCWRP).

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Identification of Viable Bacteria in Environmental Waters using EMA-qPCR

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Our research provides a simple and efficient method to identify viable pathogens in the environment. As a tool it is important because it provides an accurate description of the microbial population from any given source.

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. In the process of examining this approach it became evident that the issue of cell viability is of utmost importance. 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. These targets can be comprised of water quality indicator bacteria and/or pathogens. The method can be applied to source water, irrigation and food processing waters, as well as recreational waters and point and nonpoint discharges that enter sensitive water bodies. 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 (USFDA) and the Environmental Protection Agency (USEPA). However, EMA treatment allows amplification of target DNA from culturable, and viable but non-culturable cells, but prevents PCR amplification of DNA from non-viable or injured sources, thus avoiding the issue of DNA persistence. In the future, 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. Such a method would improve pathogen monitoring in environmental waters and potentially increase plant operation efficiencies by rapidly providing information on bacterial populations important in treatment processes. To date, we focused on wastewater effluents as these sample types have proven to be the most difficult matrices for molecular analysis.

We adopted a method based on treating our samples with EMA prior to DNA extraction in order to prevent PCR amplification of nonviable 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 from wastewater effluents. Optimization of this assay was performed by evaluating treatment with EMA concentrations of 0, 1, 2, 3, 5, 7.5 μg/ml on wastewater effluents from primary, secondary activated, and secondary trickling filter treatment processes. Our qPCR genetic targets were *E. coli* specific and identify the H7 flagellar antigen gene associated with E. coli O157:H7, *fli*C, and the beta-glucuronidase gene, *uid*A. Throughout the study, it became evident that qPCR targets were being amplified in heat-killed samples, therefore we used environmental scanning electron microscopy (ESEM) to determine if EMA was able to penetrate the cell membranes.

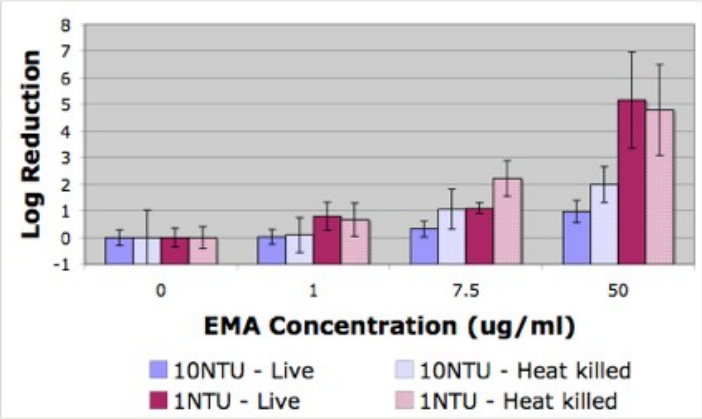

Figure 1.

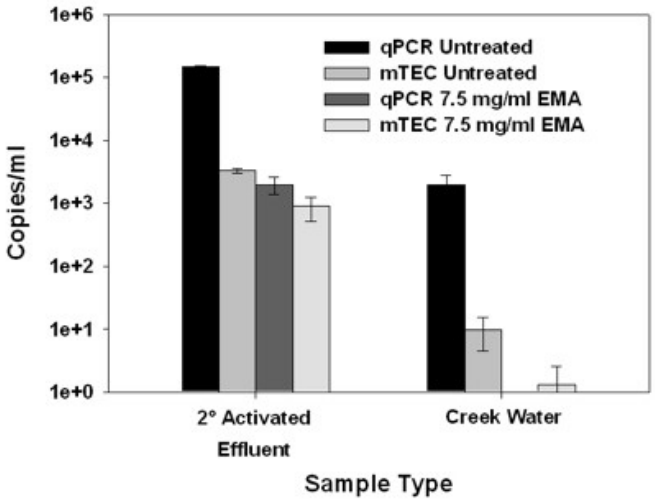

Figure 2.

Results indicated a culture age effect when treated with EMA to differentiate live and heat-killed bacteria. EMA treatment of pure cultures produced over a 4 log reduction between live and heat-killed samples treated with > 2μg/ml EMA. Additionally, the 5h and 40h cultures were most sensitive to EMA treatment. In environmental samples, EMA treatment proved to be improved after turbidity was reduced (Figure 1). Samples diluted to 1NTU were completely inhibited when treated with 50μg/ml EMA. However, treatment with 7.5μg/ml EMA produced a 1 log reduction between live and heat-killed *E. coli* from primary clarifier effluent diluted to 1NTU. However, creek water samples were completely inhibited by this concentration (Figure 2). 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. ESEM analysis allowed us to visualize the bacteria to determine if EMA concentration affected cells differently based on growth phase. Cultures at 5h, 18h, and 40h were representative of early log phase, late log phase, and early stationary phase growth, respectively. ESEM images of live bacteria treated with 7.5μg/ml were unable to produce a qualitative difference due to the limited resolution we were able to obtain.

This research is important to water quality because recreational waters such as rivers, lakes, and beaches 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 from the analysis. Wastewater treatment utilities can benefit by optimizing plant operation parameters directly based on actual bacteria populations rather than bacterial indicators. Our research provides a simple and efficient method to identify viable pathogens in the environment. As a tool it is important because it provides an accurate description of the microbial population from any given source.

Professional Presentations

Gedalanga, P.B. and B.H. Olson. Comparison of *Escherichia coli* Populations in a Lake Reservoir Enumerated using EMA-qPCR with direct DNA Analysis for Viable but Non-Culturable Bacteria and Membrane Filtration on mTEC Media. 108th American Society for Microbiology General Meeting. Boston, MA, June 1 – 5, 2008.

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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 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 groundwater protection and quality. In the area of the Santa Ana Regional Water Quality Control Board, a region of approximately 2,800 square miles and 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. For water quality professionals in the Santa Ana Region and beyond, the capacity to determine the transport and source of bacterial pathogens is essential to safeguard drinking water supplies. Therefore, 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. Additionally, such information is vital for effective design of water quality technologies including 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. Work to date has involved testing extraction methods involving ethanol, lyophilization (or freeze-drying), and sonication. The compositional analysis involves traditional 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 being utilized 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, a study is ongoing 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) flow 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. Both methods allow for a quantification of cell transport. 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 (as described above) has been compared to the transport data. To date the trend observed, regardless of cell type or environmental condition, is that the charge on the cell surface (as determined through measurement of zeta potential) 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 (aquifer sand in the column or quartz surface in the RSPF). 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; and hence, lead to more effective water management and re-use practices in the future.

Publications

Haznedaroglu, B., Bolster, C.H., and S. L. Walker "The role of starvation on bacterial adhesion and transport in saturated porous media" *Water Research* (2008) 42:1547-1554

Bolster, C.H., Haznedaroglu, B., and Walker, S. L. "Diversity in cell properties and transport behavior among 12 environmental *Escherichia coli* isolates" *Journal of Environmental Quality* (2008, in press)

Selected Professional Presentations

Chen, G., Beving, D.E., Bedi, R.S., Yan, Y. and Walker, S.L. "The Antifouling Effect of Zeolite Surfaces on Bacterial Deposition in a Parallel Plate Flow Cell" American Chemical Society 82nd Colloid & Surface Science Symposium, June 15-18, 2008, Raleigh, NC.

Gong, A.S., Benavides, M., and Walker, S.L. "Extraction and Analysis of Extracellular Polymeric Substances: Comparison of Methods and EPS Levels in Salmonella sp." 108th General Meeting of the American Society for Microbiology, June 1-5, 2008, Boston, MA

Haznedaroglu, B.Z. and S.L. Walker "Establishing the influence of starvation upon the transport of environmental *Escherichia coli* isolates" Joint American Chemical Society and American Institute of Chemical Engineers Spring Meeting, April 6-10, 2008, New Orleans, LA.

Collaborative Efforts

This effort has been in compliment to a National Water Research Institute (NWRI) grant which ended in October 2007. The NWRI grant's objective is also to identify the role of cell surface polymers on bacterial fate and transport. The combination of the Center for Water Resources and NWRI funds allowed for the full support of a graduate student, an undergraduate student researcher, and related experimental and travel expenses.

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Transport of Current-use, Sediment-bound Pesticides into a Coastal Marine System

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Current-use hydrophobic pesticides are being transported into the marine environment from agricultural and urban applications via suspended sediments from rivers. The biological effects of this transport are not known, but further study and continued monitoring will be important to aid in making informed management decisions about the use of these pesticides.

The purpose of the investigation is to assess whether current-use, sediment-associated pesticides are being transported via rivers into the shelf sediments of the Monterey Bay, if they are entering the Monterey Canyon (a deep ocean environment), and whether pesticide contributions from individual rivers can be differentiated. In conjunction with the questions about transport, it was important to determine the effects of the pesticides on biota.

Transport of Pesticides from Freshwater to Marine Environments

Three major watersheds empty into the Monterey Bay, including the mostly agricultural Pajaro and Salinas Valleys, and the San Lorenzo Valley, in which the city of Santa Cruz is located. During the major winter rain events in 2008, river water samples were collected approximately one and a half to two miles from the mouths of each river. All samples analyzed had considerable amounts of pyrethroid pesticides, however, a signature for each river was not possible, since the amounts and types of pyrethoids varied among samples taken at different times for each river. It is clear that pyrethroids are entering the marine environment during these times of high sediment transport.

Distribution of Pyrethroids in Marine Bed Sediment

Transport to the deep sea was assessed by analyzing sediment cores taken throughout the Monterey Canyon with a remote operative vehicle. Analyses of canyon sediments are still in progress, but work to date has found little or no evidence of pyrethroids reaching the deep sea.

Marine benthic grab samples were taken on the continental shelf along transects coming out of each river mouth, and along the 80 and 50 meter isobaths. Due to the hydrophobicity of pyrethroids it was hypothesized that the area of major sediment deposition, found at the 80 meter isobath, would be the area of highest pyrethroid concentration. The transect samples coming out of each

river were taken to test the possible extent of influence of each of the rivers examined. Chemical analysis of sediments indicated only possible trace amounts of pyrethroids on the continental shelf.

Toxicity tests of the shelf samples were performed with a common marine sediment toxicity testing amphipod, *Leptocheirus plumulosa*, a species that preliminary data indicates is sensitive to pyrethroids. These tests showed no toxicity to the test organisms.

Finally, sediments from Elkhorn Slough, a coastal embayment in to which the Salinas River flows, were tested. Pesticide analysis is still in progress, but sediment toxicity was found in those portions of the Slough most affected by river inputs.

Significance of Findings

Transport of pyrethroids from fields into nearby freshwater streams is well documented. However, this study shows the transport of pyrethroids much further downstream into the marine environment. Results to date indicate sediment toxicity in enclosed coastal areas heavily affected by river discharges, but mitigation of this toxicity with the dilution occurring on the open continental shelf. Whether the toxicity observed is due to pyrethroids will not be known until the chemical analyses are completed.

Sampling was conducted in spring 2008, but the winters of both 2008 and 2007 were characterized by unusually low rainfall. While we demonstrated that suspended sediment entering the Bay carries with it pyrethroids, the low flow of the rivers resulted in relatively little sediment entering the Bay in those years. This low flow would mean that this year's sampling probably underestimated the typical amount of pyrethroid transport occurring and its effects on coastal waters. Thus, it will be important to further monitor pyrethroids in riverine discharges, and we anticipate performing analysis of archived samples from other years with higher rainfall and greater sediment transport.

Collaborative Efforts

The Monterey Bay Aquarium Research Institute (MBARI), particularly Dr. Charlie Paull and Dr. James Barry, provided ship and ROV support for collection of the deep sea material. The Central Coast Long-term Environmental Assessment Network (CCLEAN), a monitoring program supported by dischargers to Monterey Bay, helped arrange boat time on the R/V Fulmar, a ship operated by NOAA's Monterey Bay National Marine Sanctuary. Finally, Moss Landing Marine Laboratories provided the use of the R/V John Martin for collection of sediments throughout Monterey Bay.

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Modeling Non-Point Source Contributions of Host-Specific Fecal Contamination in San Pablo Bay

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This study combines microbial source tracking, pathogen analysis, and validated ultrafiltration technology with a solid 3-D modeling approach for a case study of San Pablo Bay. One of the outcomes of the project is a model for fate and transport of microbial markers that can be used directly in San Pablo Bay and, with some modifications, in other water bodies.

Fecal contamination from point and non-point sources into coastal and estuarine waters is a problem of increasing concern in the United States, as it affects public health as well as the coastal environment. Appropriate action cannot take place without precisely quantifying the contaminant concentrations and identifying the sources, whether from urban, farm, or wildlife areas. This study combines microbial source tracking (MST), pathogen analysis, and validated ultrafiltration technology with a solid 3-D modeling approach for a case study of San Pablo Bay (SPB). One outcome of the project is a model for fate and transport of microbial markers that can be used directly in SPB and, with some modifications, in other water bodies. Potential end users include water control boards, managers of recreational lands and natural resources, personnel in wastewater treatment facilities, and others involved in water quality monitoring.

The main project objectives are outlined below:

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

We recently began testing a new SYBR Green-based qPCR assay, published by Lu et al. (2008), targeting the bacterial species *Catellicoccus marimammalium* on fecal samples obtained in California from a variety of sea birds, marine mammals, and terrestrial animals. The assay gave highest sensitivity for fecal extracts from Western gulls, with up to 5 orders of magnitude lower sensitivity for other sea birds. Signals from other mammals showed either 5 orders of magnitude lower sensitivity or were below detection. The different sensitivities suggest that this assay can detect general fecal pollution stemming from sea birds and that mammals are detected rarely, if at all. We have tentatively concluded that the assay can be used to estimate the contribution of fecal material from sea birds to SPB.

Provide data for modeling purposes on environmental concentrations of Bacteroidales and selected pathogens.

We completed 6 water sampling events from November 2007 through July 2008 at a total of 10 sampling locations. We applied a technique of MST utilizing an anaerobic bacterial order *Bacteroidales*, which is prevalent in mammals' gastrointestinal systems, as an animal-specific source indicator for fecal contamination. With our validated quantitative real-time PCR assays to identify fecal contamination contributed from all mammals, human, cow, and dog, together with the use of large-volume (100 L) hollow-fiber ultrafiltration, we are monitoring *Bacteroidales*, traditional fecal bacterial indicators (*E.coli* and Enterococci), and selected human pathogens in SPB.

Universal *Bacteroidales* markers were detected in all samples, indicating non host-specific fecal contamination. This 100% detection contrasted with the partial detection of *E. coli* (15 of 38 samples; 39.5%) and Enterococci (9 of 38 samples; 23.7%) during events 2 to 5.

Human-specific *Bacteroidales* were detected in 31 of 46 (67.5%) of samples. Cow- and dog-specific *Bacteroidales* were below detection limits in all samples except one from event 2 where the dog genetic marker was detected. It is possible that some fecal contamination of SPB may have originated from other sources

for which the appropriate host-specific assays have not yet been developed. To address this hypothesis, we will use DNA markers specific for sea birds (Lu et al. 2008) in all water samples. Concentrations of viral pathogens adenoviruses and enterovirus were not detected at any sampling location.

Determine the rate of decay of animal host-specific molecular markers (16S rRNA genes) under environmental conditions by performing microcosm studies.

We completed field measurements of persistence and survival of host-specific *Bacteroidales* cells and their DNA in the seawater environment under sunlight and dark conditions. A two-stage exponential-plus-linear model was used to fit the experimental decay data and to calculate the decay rates as well as T_{99} (time for 2-log reduction). The decay curves were compared and non-linear regression analysis was performed. The decay rate will be used to establish a fate and transport model for host-specific *Bacteroidales.*

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 to identify the sources of that contamination.

We have developed hydrodynamic simulations to characterize the flow in SPB. These simulations are the basic input for the advective transport of *Bacteroidales*. We have tested the response of the model to variations in several parameters. We are also developing comparisons of results with our Si-3D and models of others. The main flow features are well reproduced. Sub-routines for the simulation of transport of *Bacteroidales* have been improved significantly and are operative. Hydrodynamic and water quality scenarios are being defined and runs are being developed.

Based on results obtained thus far from the hydrodynamic and water quality models, and with the help of satellite images, we have determined the existence and location of three “flow corridors” for the transport of substances in SPB. More work in this regard is under way.

Publications

Bombardelli, F. A., and Jha, S. K. Hierarchical modeling of the dilute transport of suspended sediment in open channels. *Environmental Fluid Mechanics*, in press. (Online 9/11/08).

Selected Professional Presentations

Wuertz, Stefan, Probability Analysis of Microbial Source Tracking (MST) Data, U.S. EPA Workshop on Microbial Source Tracking, Cincinnati, OH, July 2007.

Collaborative Efforts

Additional funding from the Cooperative Institute for Coastal and Estuarine Environmental Technology greatly aided collaborative research and outreach activities. Dr. Drew M. Talley, research coordinator at Romberg Tiburon Center for Environmental Studies (RTC), San Francisco National Environmental Research Reserve recommended sampling sites, which were integrated into the ten sampling locations in SPB. Dr. Talley also facilitated the use of a research vessel through the San Francisco State University Marine Operations. With the assistance of David Bell, Marine Superintendent/Dive Safety Officer, and David Morgan, vessel operator, a vessel suitable for oceanographic research was used for sampling.

The first outreach workshop was facilitated by Marina Psaros, a coastal training program coordinator from the RTC. A website with project information and updates is hosted at: http://www.sfbaynerr.org/ctp/programs/program_detail.php?PROGID=Fe.

Tina J. Low, P.E., of the San Francisco Bay Regional Water Board, and Ken Poerner, a land steward from Solano Land Trust, have provided valuable feedback on the project’s potential applicability and challenges.

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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.

Assessing the Effectiveness of California's Underground Storage Tank Annual Inspection Rate Requirements

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(*Dr. Cutter has since moved to Pomona College)

Preliminary results show that the underground storage tank inspection mandates in SB 989 increased inspection rates in California cities and counties. However, preliminary results do not indicate any effect on underground storage tank leak rates compared to a control set of jurisdictions.

Underground fuel Storage Tanks (USTs) have long posed a serious threat to California's groundwater resources. In response, California has instituted a variety of tank construction, operation and inspection requirements. California mainly relies on local jurisdictions (counties and some cities) for inspections of UST facilities. A key element of California's current inspection regime, mandated by SB 989, is that these jurisdictions inspect UST facilities at least annually beginning in Fiscal Year 2001.

The data indicates that the inspection mandate of SB 989 was effective at increasing inspections. Jurisdictions that averaged less than one inspection per year in the pre-mandate period (1998-2001) had a statistically-significant increase in their inspection rates from the pre-mandate to the post mandate period (2001-2004). Inspection rates increased from about .82 inspections per year to 1.19 inspections per year, or an increase of 44%. Those jurisdictions that averaged at least annual inspections before 2001 saw their rates increase by 11% to 1.5 inspections per year. The much greater increase in the group which was most likely impacted by the mandate suggests that SB 989 did have a significant impact on inspection rates.

However, it is difficult to say whether the inspection rate mandate actually decreased leaks. We tested the effect of the mandate by analyzing whether those jurisdictions subject to the mandate (i.e. those below one inspection/year) had larger decreases in their leak rates than those not subject to the mandate by comparing the leak rate in the period directly before the mandate (1999-2001) to the period since (2002-2004). Both the absolute decrease and the percentage decrease in rates are similar for the two sets of jurisdictions. Previously compliant jurisdictions had a decrease of .05 leaks per year per facility or a 60% decrease. Newly compliant jurisdictions had a decrease of .03 leaks per year per facility or a 37% decrease.

The next step of the analysis is to compare similar retail gasoline facilities across jurisdictions that were and were not affected by the inspection mandate to determine the effect of inspections on matched facilities. The results of that work will be reported in the final report.

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Securing Access to Water: Institutional Strategies for Coping with Drought

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Analysis of the legal, institutional and management issues surrounding particular strategies to augment water supply during a drought – groundwater recharge, storage, and conjunctive management – resulted in a proposal to establish a strategic groundwater reserve to mitigate severe water shortages. The California Constitution, Article X, Section 2 and other sections of the California Water Code, give the state the authority to establish the reserve, which would involve creating incentives to 1) bring groundwater basins into hydrologic balance through recharge processes, 2) promote the enhancement of groundwater storage, and 3) establish and maintain a groundwater reserve supply.

Confronting Drought:

Water supply planning and the establishment of a strategic groundwater reserve

The first year annual report covers research on water supply planning in the state and examines strategies to reduce vulnerability to a long-term drought. Precipitation in California varies from year to year including extended dry periods, and evidence is also accumulating that global climate change will impact the state's water resources and increase the number and severity of future drought episodes. At the same time, ongoing population growth and claims to water by more diverse interests have increased demands on the state's water supplies. While the two conditions are related, as the impacts from global warming and periodic droughts will intensify demand-induced water shortages, to a large extent researchers and policymakers have failed to focus on strategies that could mitigate both conditions, and some solutions proposed to address demand generated water problems could create increased water shortages when a severe dry period does occur.

The first year of research examined the fragmented system of water supply planning in California, including the management of state and federal water projects, the most recent draft state water plan, urban water management planning, and local groundwater management planning. Significant areas of disconnect were uncovered between planning for a prolonged drought and planning to accommodate the state's burgeoning demand for water. Planning for a drought, including generating surface and groundwater data and preparing and implementing water shortage contingency plans, is primarily response oriented. Planning for ways to generate additional water to satisfy increasing demand includes strategies such as desalination, recycled water, water use efficiency, and the construction of new storage and conveyance systems. While often described as also creating water for dry periods, a central concern is that if water generated through these latter strategies is primarily utilized to support increased demand, the outcome could be an eventual upsurge in overall water demand in the future along with a hardening of demand side conservation strategies. This could actually increase vulnerability to water shortages when a severe dry period does occur. Analysis of the legal, institutional and management issues surrounding alternate strategies to augment supply – groundwater recharge, storage, and conjunctive management – led to a proposal to establish a strategic groundwater reserve as a key strategy to mitigate severe water shortages.

This would involve creating incentives to 1) bring groundwater basins into hydrologic balance through recharge processes, 2) promote the enhancement of groundwater storage, and 3) establish and maintain a groundwater reserve supply. The reserve would only be withdrawn and used during a severe dry period and is critical to conserving nature's capital for the inevitable long-term drought. Conjunctive management methods could be redesigned to encourage recharge processes, to augment supply, and most important to safeguard the strategic reserve from being overdrawn during normal rainfall years. The legal authority presently available to the state to achieve the establishment and maintenance of healthy groundwater aquifers including a strategic groundwater reserve was detailed, focusing on the California Constitution, Article X, Section 2, and sections of the California Water Code. Local authority to establish these goals was also detailed, given the political resistance so far to state regulation. Although large financial assistance programs have been put in place for local communities to implement groundwater improvement programs, groundwater overdraft and deteriorating quality remain significant problems. To address the consequences of a potential severe drought, research suggests that planning must move beyond the general notions of reducing water use when a drought occurs. In thinking proactively about reducing vulnerability to a drought through the establishment and maintenance a strategic water reserve, this research contributes to the debate over how to live sustainably in a fundamentally dry landscape.

Professional Presentations

Langridge, Ruth "Confronting Drought: Water supply planning and the establishment of a strategic groundwater reserve" Groundwater Resources Association, Climate Change Symposium, Sacramento CA, August, 2008.

Collaborative Efforts

Discussions with:

Joseph Sax, Professor Emeritus, Boalt Law School, University of California, Berkeley

Andrew Fisher, Professor, Earth Sciences, University of California, Santa Cruz

Robert Gottlieb, Professor and Director of the Urban and Environmental Policy Institute, Occidental College, California

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Integrated Regional Water Management Planning in California: Developing Institutions for Collective Action

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Integrated Regional Water Management in California is one of the most prominent institutional mechanisms being used to encourage cooperation in fragmented water management contexts. Our analysis of the Bay Area IRWMP finds mixed success; it did not increase collaboration or integration, but did build networks and trust necessary for the further evolution of cooperation and identified projects consistent with stakeholder priorities.

The goal of this project is to use theories of institutions and collective action to understand the factors contributing to the effectiveness of Integrated Regional Water Management Planning (IRWMP) in California. IRWMP provides state grant funding to local stakeholders to develop integrated regional water management plans. These plans are designed to encourage cooperation and integration within the fragmented institutional setting that has traditionally characterized water management in California.

The research focused on the Bay Area IRWMP, and used personal interviews of key participants, a quantitative survey of over 200 stakeholders, and analysis of priority water projects. We evaluate the effectiveness of IRWMP by focusing on three factors: levels of collaboration/participation, integration, and project effectiveness. Data collection was completed in June 2008, and our preliminary analysis finds mixed support for the effectiveness of IRWMP. Stakeholders are generally dissatisfied with the process, especially the role of the state government. Participation in IRWMP does not appear to increase overall levels of collaboration. Integration mainly occurs within functional domains such as water supply and flood control, and there is little integration with ecological issues. Environmentalists and watershed groups believe that IRWMP is not fair to their interests.

On the other hand, stakeholders indicate that IRWMP has increased levels of trust and policy networks, which may be critical to

Table 1: Perceptions of IRWMP Goal Attainment by Functional Area

Program Goal:	TCC	Water Supply	Waste Water	Flood Protection	Watershed Habitat
Mitigating conflict among stakeholders.	3.84	4.27	3.67	4.09	3.75
Improving water supply reliability.	3.18	3.00	3.33	3.33	3.86
Improving water quality.	3.05	2.83	3.00	3.33	3.47
Protecting or restoring wildlife habitat.	3.26	2.91	3.18	3.58	3.29
Improving water management in disadvantaged communities.	2.71	3.11	3.33	3.27	3.00
Improving hydrologic function.	2.82	2.70	2.91	3.00	3.12
Integrating water and land use issues.	2.91	2.85	2.77	2.83	2.85

Note: Cell entries are average scores from the following question: "Based on your experiences with IRWMP, pleas rate how well IRWMP has contributed to achieving the following water management goals, where 1=No contribution and 7= major contribution to achieving goals."

Table 2: Opinions about Effectiveness of IRWMP by Functional Area					
	TCC	Water Supply	Waste Water	Flood Protection	Watershed Habitat
IRWMP has improved collaboration among stakeholders.	4.78	5.00	5.00	5.00	4.84
IRWMP has increased availability of funding for my organization.	3.39	4.37	4.07	3.57	3.23
IRWMP was too time consuming.	4.58	4.53	4.73	4.87	4.78
IRWMP was fair to all stakeholders.	3.38	4.00	4.00	3.77	3.05
IRWMP was controlled by narrow interests.	4.39	3.81	4.07	4.33	4.50
IRWMP helped me network with other stakeholders.	5.48	5.25	5.47	5.40	4.92
The IRWMP process has effective leadership.	3.65	4.71	4.62	4.53	3.76
State guidelines for IRWMP were clear and understandable.	2.78	2.80	3.14	3.21	3.13
State guidelines for IRWMP were sufficiently flexible to accommodate regional differences.	2.96	2.93	3.23	3.15	3.14
IRWMP included all appropriate stakeholders.	3.91	5.07	4.92	4.46	3.91
State guidelines for IRWMP provided enough time for planning.	3.13	3.92	3.55	3.50	3.29
IRWMP has generally improved water management in the Bay Area.	3.63	3.77	3.46	3.73	3.35
My participation in IRWMP had a large influence on decisions.	2.88	3.43	3.23	3.25	2.88
IRWMP has increased the level of trust among water management stakeholders.	4.18	4.46	4.08	4.42	3.90
The IRWM planning process would be more effective if it were limited to smaller geographic areas.	4.44	5.00	4.00	5.21	4.47

Note: Cell entries are average scores from the following question: "Based on your experience with the IRWMP program, please rate your level of agreement or disagreement with the following statements about the IRWMP process, where 1=Strongly Disagree and 7=Strongly Agree."

future water management decisions. It may be too early to expect widespread increases in integration and collaboration; building an initial basis may be enough for now. Furthermore, the distribution of priority projects that emerged from the IRWMP planning process is relatively consistent with stakeholders' issue priorities. However, the actual money available for implementing these projects was heavily skewed towards previously existing projects from water supply and flood management sectors.

Collaborative Efforts

In-kind contributions came from DWR staff, plus over 20 Bay Area IRWMP stakeholders who were interviewed for development of the quantitative survey.

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Enforcement-Driven Financing of Water Quality in California: The Case of Supplemental Environmental Projects

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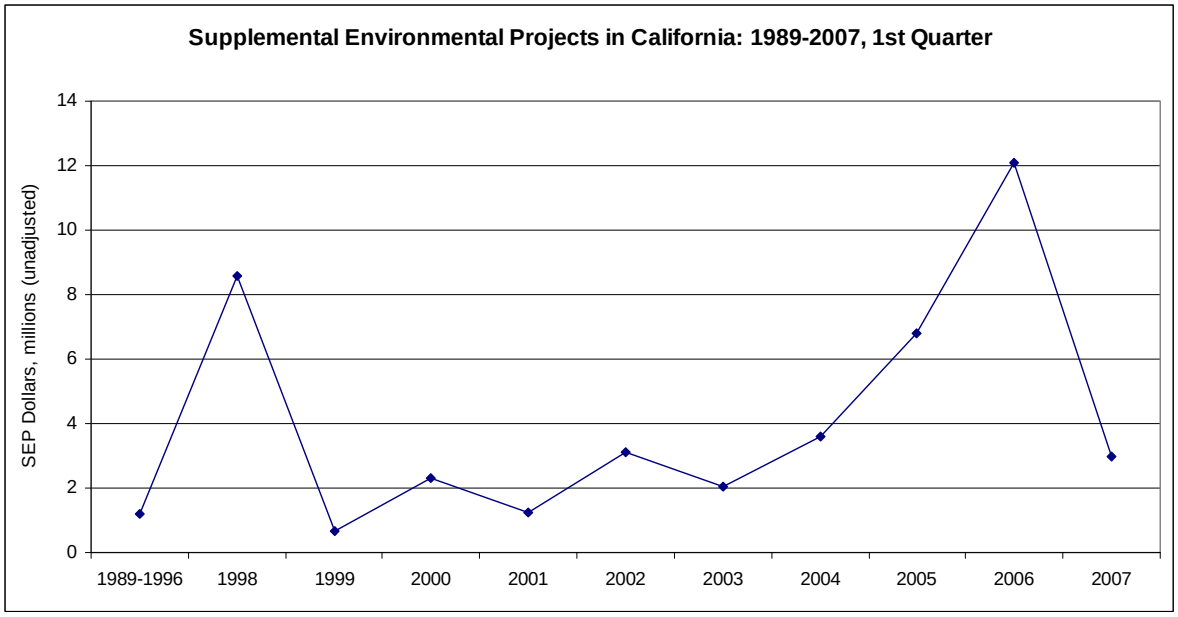
This project evaluates California's experience with Supplemental Environmental Projects (SEPs), primarily as they are implemented by the nine regional water quality control boards, focusing on 1) the extent and variation of SEP activity throughout the state, 2) the proportion of enforcement fines being re-directed to SEPs, 3) the parties involved, and 4) the environmental outcomes of SEPs and whether they generally and reliably improve water quality. The 9 regional boards approved approximately 300 SEPs between 2004 and 2007 representing over $47 million of water quality project funds that might not otherwise have been used for cleanup, restoration or improvement programs.

Since the early 1990s, US Environmental Protection Agency guidelines allow states to direct some enforcement fines to Supplemental Environmental Projects (SEPs) in lieu of paying these sums into state general funds or cleanup and abatement accounts. The US EPA established guidelines governing SEPs in 1998. These require that 1) there is a nexus between the discharge violation and environmental benefits arising from a SEP, 2) the SEP must improve protection or reduce risks to public health of the environment, and 3) the SEP must consist of a project that violators would otherwise not have performed.

This project evaluates California's experience with SEPs, primarily as they are implemented by the nine regional water quality control boards. The central inquiries include 1) the extent and variation of SEP activity throughout the state (i.e., do the regional boards vary in their elective use of SEPs; has SEP use increased or decreased in recent years), 2) the proportion of enforcement fines being re-directed to SEPs, 3) the parties involved (e.g., are violators primarily implementing their own SEPs or are third parties doing so? If third parties are taking the lead, how are they getting involved?), and 4) what are the environmental outcomes of SEPs; do they generally and reliably improve water quality?

To date, the research team has collected SEP data from all regional boards; however, considerable work remains to verify the information gathered as the quality of records varies tremendously. According to these data, California's nine regional boards approved approximately 300 SEPs between 2004 and 2007 representing over $47 million of water quality project funds that might not otherwise have been used for cleanup, restoration or improvement programs. As expected, the regional boards vary widely in their use of SEPs, from a low of 5 SEPs with a total cost of $228,000 in region 7 (Colorado River Basin) to a high of 70 SEPs with a total cost of $12.5 million in region 3 (Central Coast). Some regions see only 10-15% of their Administrative Civil Liabilities (ACLs) going to SEPs; for others, SEPs can represent over 80% of the fines paid for an enforcement action.

In addition to these SEP enforcement program statistics, the team completed in-depth interviews with 10 staff members in regions 1, 2, 3, 4, 6, and 8. On the project implementation side, interviews were completed with 11 SEP implementing parties, including



staff from water districts, wastewater treatment plants, habitat restoration groups, land trusts and wetlands managers. In some regions, staff actively maintain lists of SEPs that they would like to see funded; thereby, having ready-made programs to which settlement funds can be directed. Third parties, including non-governmental organizations, municipalities and businesses throughout the state all participate, to varying degrees, in proposing viable projects.

At the statewide level, the future of SEP programs is very much in question. Citing concerns about accountability and oversight, the State Water Resources Board has been considering reducing the amount of an ACL that can be spent on a SEP down to as low as 25%. In year two of this project, the research team will be investigating the efficacy and oversight dimensions of SEPs, which will allow the PI and colleagues to help inform these new enforcement policy proposals as well as SEP "best practices."

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Special Projects

These projects may address an emerging issue or may capitalize on opportunities for the advancement of water science outside of the standard call for proposals.

Maintenance and Dissemination of a Water Transfer Data Base for 12 Western States, 2005-2008

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With the West's limited freshwater supplies facing increasing pressure at a time of perhaps more variable supply, effective water management and allocation are more critical issues. The Water Transfer Data Base is the most comprehensive data set available for analyzing the extent and pattern of voluntary water market exchanges across states and time.

The project involves collaborative work between Gary Libecap and a graduate student, Zachary Donohew, to compile and maintain the largest comprehensive, publicly-available data set on water transfers and water markets for researchers and policy analysts. The data are drawn from the *Water Strategist* for 12 western states (Washington, Oregon, California, Arizona, Nevada, Utah, Idaho, Montana, Wyoming, Colorado, New Mexico and Texas) from January 1987 – May 2008, as of this time. There are over 3,400 observations of water transfers that include amount of water, contract type (short-term lease, long-term lease, and sale), parties involved, origination use, destination use, and price (2,530 observations). The methodology is described and data categories are presented in a Word document along with an excel file of the trades placed on the Bren School Website and linked to the Bren website at http://www.bren.ucsb.edu/news/water_transfers.htm and the Center for Water Resources' website at http://www.lib.berkeley.edu/WRCA/WRC/research_sp.html. The data set is advertised on the Bren School webpage and the website describes the dataset as follows:

"With the West's limited freshwater supplies experiencing increasing pressure from agricultural, environmental, recreational, and urban demands, as well as the effects of climate change on precipitation patterns, effective management of water is becoming a more critical issue. Private leases and sales of water as part of water markets provide one option for water management. The Water Transfer Data Base, funded by the National Science Foundation and the California Water Resources Research Center and presented by the Bren School, is the only comprehensive accounting of water trading between 1987 and 2008 in the 12 Western States. As such, it is a valuable tool for researchers and others interested in the extent and pattern of voluntary water exchanges in the West. The data include trades involving agriculture, urban, recreational, and environmental uses; the number and amounts of water involved; and the prices paid. Presenting these data as a public service is an important part of the extension mission of the University of California, as well as that of the Water Policy program at the Bren School."

The dataset and website are continually updated.

Publications

Donohew, Zachary, "Property Rights and Western U.S. Water Markets," *Australian Journal of Agricultural and Resource Economics*, in press.

Brewer, Jedidiah, Robert Glennon, Alan Ker and Gary D. Libecap "Water Markets in the West: Prices, Trading and Contractual

Forms," *Economic Inquiry* 2008, 46(2): 91-112.

Brewer, Jedidiah Brewer, Michael Fleishman, Robert Glennon, Alan Ker, and Gary D. Libecap. "Law and the New Institutional Economics: Water Markets and Legal Change in California, 1987-2005," *Washington University Journal of Law and Policy* 2008, 26 (August).

Brewer, Jedidiah, Robert Glennon, Alan Ker and Gary D. Libecap "Transferring Water in the American West: 1987-2005," *Michigan Journal of Law Reform* 2007, 40(4): 1021-53.

Professional Presentations

Libecap, Gary D., Law and New Institutional Economics: Water Markets and Legal Change in California, 1987-2005, Mapping the Legal Frontiers of New Institutional Economics, University of Colorado Law School, Boulder, June 2008.

Libecap, Gary D., Water Markets as Tool for Addressing Water Shortages, Meeting on "Is there a Water Crisis in Los Angeles?" Association of California Water Agencies and Young Presidents Organization Meetings, La Canada, CA, May 2008.

Libecap, Gary D., U.S. Water Allocation and Water Markets, National Bureau of Economic Research-India Conference, Neemrana India, January 2008.

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http://www.bren.ucsb.edu/people/Faculty/gary_libecap.htm

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.

Application of Redox Mediators to Accelerate Removal of Selenium from Agricultural Drainage Water

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The redox mediator, AQDS, accelerates the conversion of Se(IV) to elemental selenium thereby increasing the removal rate of total soluble Se from agricultural drainage water.

Agricultural drainage water contributes to selenium (Se) contamination of aquatic systems in California's San Joaquin Valley. The bioaccumulation of Se in aquatic systems creates serious hazards to fish and waterfowl. This project builds on previous work to identify ways to remove or reduce Se from agricultural drainage water before it is disposed into aquatic systems.

Redox mediators have been used as electron carriers to stimulate the reductive biotransformation of environmental contaminants by shunting electrons between an external electron donor and the contaminants. Three redox mediators, anthraquinone-2,6-disulfonate (AQDS), hydroxyl-p-naphthoquinone (HNQ), and naphthoquinone (NQ), were assessed in the reduction of Se(VI) (1000 µg/L) to Se(0) by *Enterobacter taylorae* in drainage water containing a sucrose level of 500 mg/L. The results showed that addition of neither HNQ nor NQ increased the reduction of Se(VI) to Se(0). AQDS was found to enhance the removal of total soluble Se, though not directly through reduction of Se(VI) to Se(0). During an 8-day experiment, about 90% of the added Se was removed from drainage water with AQDS. Addition of AQDS to drainage water only increased the removal of Se(IV), not Se(VI), suggesting that the increase in the removal of total soluble Se in drainage water is caused by rapid removal of Se(IV) in the presence of AQDS.

We will continue this study by using zero-valent iron to enhance bacterial removal of Se from drainage water and to limit the formation of the most bioavailable organic Se.

Publications

Zhang, Y.Q. Z. A. Zahir, C. Amrhein, A. Chang, and W.T. Frankenberger, Jr. 2007. Application of redox mediator to accelerate selenate reduction to elemental selenium by *Enterobacter taylorae*. J. Agric. Food Chem. 55:5714-5717.

Professional Presentations

Invited Presentation: Redox reactions of chromium, uranium, selenium, and arsenic in soils. Universität für Bodenkultur Wien (University of Natural Resources and Applied Life Sciences). Department of Forest- and Soil Sciences, Vienna, Austria. May 8, 2007.

Collaborative Efforts

This project has helped us obtain additional funding from the California Department of Water Resources to study the fate of selenium and nutrients in shallow ponds at the Salton Sea. Collaborators on this project are Professors Michael Anderson and Daniel Schlenk (UCR).

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Data Assimilation for Shallow Water Flows using Lagrangian Sensing

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Julie Perceley, Tarek Rabbani, Issam Strub, Alexandre Bayen
Civil and Environmental Engineering
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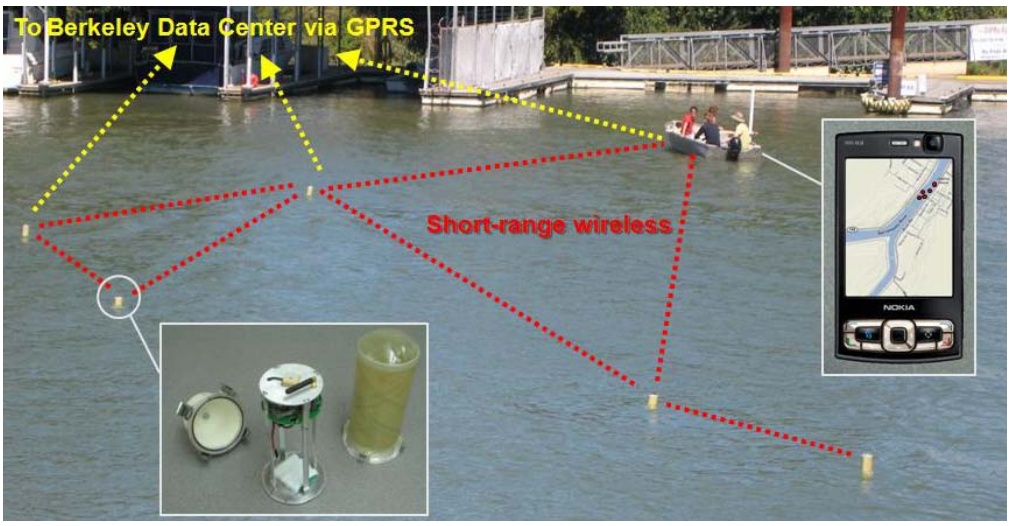
The goal of this project is to design, implement and test algorithms to be able to reconstruct two dimensional shallow water flows using Lagrangian (mobile) sensors. The project also includes an experimental component with hardware – software development and deployment as part of field operational tests in the San Joaquin – Sacramento Delta.

The main objective of this project is to create a set of hardware and software tools which can be deployed quickly in a flexible manner to perform Lagrangian measurements in the Sacramento – San Joaquin Delta. Our group is working on the development of a hardware platform (drifters), which can measure velocity, transmit data in real time to a base station using GSM modules, and perform onboard computing (using a Linux gumstix). Additional sensors can easily be added to the hardware platform developed for the project. The floaters have an underwater sail to capture subsurface currents should that information be desired. Based on measurements provided by the drifters, we are interested in developing inverse modeling algorithms to reconstruct currents and other features, such as salinity, in real time. This relies on an accurate modeling of the deployment areas (using Shallow Water Equations), on which we can add additional one way coupled models. The inverse modeling algorithms under development for the project rely on a proper discretization of the flow equations, and the formulation of an optimization program in which we try to minimize discrepancy between measured and estimated quantities. In the case of the full nonlinear problem, we solve the data assimilation problem using Ensemble Kalman Filtering, a technique capable of handling the nonlinearity of the equation. Under specific assumptions relevant for the Sacramento Delta, we are able to simplify the equations and use either spectral methods (directly applicable to data reconciliation) or quadratic programming.

We implement our algorithms directly in twin simulations, using shallow water solvers such as Mike and Telemac. These twin experiments are used to assess the accuracy and the efficiency of the proposed



methods. The hardware platform deployed in the study is used to gather Lagrangian data in the Georgianna Slough (Walnut Grove), which serves as a testbed for this study. This area is of particular interest due to the tidal inversion it exhibits. The data collected from GPS is fused with additional data available to us through the USGS sensors already deployed in the Delta, or through Eulerian sensors available to us from other grants. Recently, we have started exploring active sensing by adding self propelled drifters and a submarine to our fleet.

Publications

Olli-Pekka Tossavainen, J. Percelay, A. Tinka, Q. Wu and A. M. Bayen, Ensemble Kalman filter based state estimation in 2D shallow water equations using Lagrangian sensing and state augmentation, *2008 IEEE Conference on Decision and Control*, Cancun, Mexico, Dec. 2008

Qingfang Wu, X. Litrico and A. Bayen, Data Reconciliation of an Open Channel Flow Network using Modal Decomposition, *2008 IEEE Conference on Decision and Control*, Cancun, Mexico, Dec. 2008.

Simon Munier, Q. Wu, S. Amin, A. Bayen, X. Litrico and G. Belaud, Parameter identification for the shallow water equations using modal decomposition, *2007 IEEE Conference on Decision and Control*, New Orleans, LA, Dec. 2007.

Qingfang Wu, X. Litrico and A. Bayen, Data Reconciliation of an Open Channel Flow Network using Modal Decomposition, *Advances in Water Resources,* In Press (available online Nov. 2008).

Professional Presentations

Alexandre Bayen, Data Assimilation for two dimensional shallow water flows using Lagrangian Sensing, Workshop on Networks of Irrigation Channels, Maiori, Italy, October 2008.

Andrew Tinka, Development, testing and prototyping of a Lagrangian sensor platform, Center for Entrepreneurship, March 2008.

Alexandre Bayen, Motion tracking in large scale infrastructure systems using smartphones, CITRIS research exchange, UC Berkeley, May 2008.

Qingfang Wu, Parameter identification for the shallow water equations using modal decomposition, 2007 IEEE Conference on Decision and Control, New Orleans, LA, Dec. 2007.

Collaborative Efforts

Through the France Berkeley Fund, Dr. Xavier Litrico, from the CEMAGREF Agricultural Agency in France spent one year at Berkeley working on the modeling of the water channels under tidal forcing. PhD student Tarek Rabbani worked in France for a month at CEMAGREF to pursue this effort.

The Laboratory of Aquatic Technologies at the University of Porto in Portugal brought a light autonomous underwater vehicle to Berkeley in the fall of 2008 to perform some autonomous navigation and sensing experiments with us in the Georgianna Slough in Walnut Grove. This interaction will continue in Fall 2009.

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Mechanisms of Boron Toxicity in Crop Plants

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Boron toxicity is an important constraint to the use of saline irrigation waters in agriculture. Our goal is to determine the mechanism of boron toxicity, to identify the best tissue to utilize for crop monitoring and to define which stage of crop growth and which tissue is most, and least sensitive to excess boron in irrigation waters.

Boron toxicity is a problem threatening significant areas of agricultural production in California and limiting the reuse of drainage waters. Research into the management of B has been plagued by results that are inconsistent, contradictory and difficult to interpret primarily because we do not know why B is toxic to plants and we do not know how to measure crop B and its relationship to the occurrence and impact of B toxicity. Based upon recent findings of the role of B in plants, we hypothesized that root and shoot extension (meristematic) growth would be the most sensitive indicator of boron toxicity. This project aims to identify the mechanism of B toxicity, and to develop the sampling strategies and standards necessary for field research and crop management.

Two experiments have been completed and a third is underway. Experiments one and two were conducted in growth chambers in one gallon pots with potting media:sand mixture. Plants were grown for four weeks at applied boron concentrations ranging from adequate (0.05, 0.25 mM), to concentrations observed in field conditions (0.5, 1.0, 2.5 mM) and extreme concentrations frequently used in experimentation (5.0, 7.5 and 10 mM). Key findings of these experiments highlight the critical difference in crop response to B concentrations found in field conditions from those observed under artificially high B supply.

Under conditions likely to be found in field settings (B in soil solution at 0.25, 0.5, 1.0 and 2.5 mM), we observed that shoot and root growth (total dry weight production) were equally sensitive to the impact of increasing B in the growth media (Fig. 1). Significant negative impacts of B on crop growth were observed at B concentrations of 0.5 mM and higher. At these concentrations, visual symptoms of boron toxicity were restricted to marginal and leaf tip burn on the oldest leaves and slight chlorosis on old leaves at the highest of these B concentrations (2.5 mM).

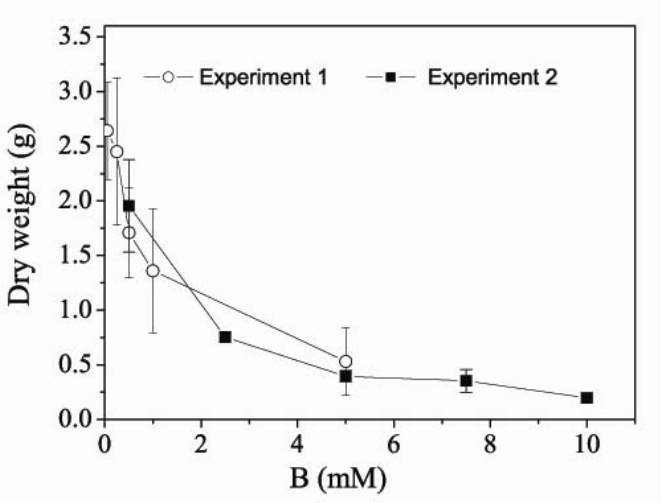

Figure 1. Influence of boron treatments on dry weight of roots of tomato. Plants were grown for 28 days with normal boron supply (0.05 mM) prior to application of treatments. Plants were harvested at day 56. Results of two replicate experiments are presented.

When B was applied at concentrations far greater than occur in agricultural settings (but equivalent to concentrations used in prior experiments) we observe that the symptoms of B toxicity are different from those observed in the field or at concentrations of less than 2.5 mM. When B is applied at these acute levels (5.0, 7.5, 10.0 mM), chlorosis and necrosis occur rapidly (3-7 days) and are distributed throughout the plant. At the extreme B treatment levels, entire leaf collapse and death can occur within 5 days. Very significant (>80%) shoot and root growth inhibition is observed at these B concentrations. These results illustrate that previous experimentation conducted at unrealistic boron concentrations results in misleading conclusions.

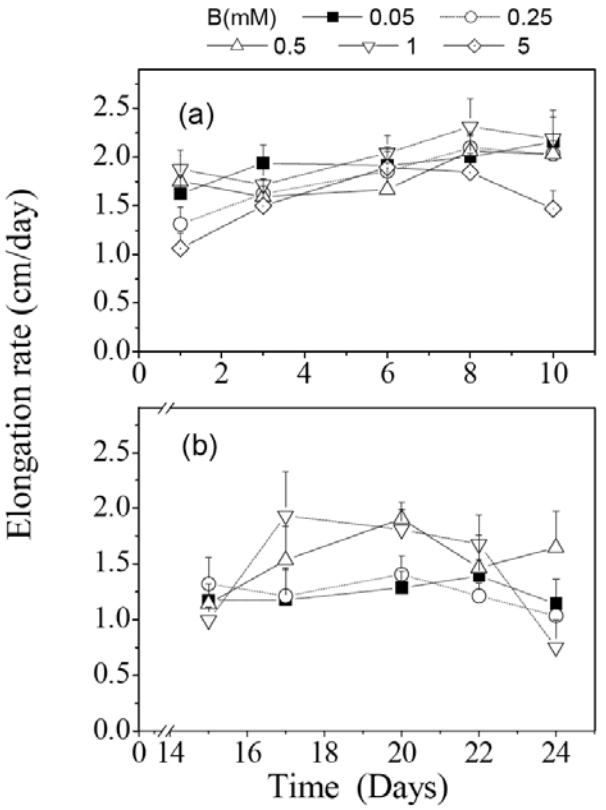

Figure 2. Influence of boron on rate of leaf elongation in youngest expanding leaf tissue. Plants were grown for 28 days at normal B supply (0.05 mM) prior to application of treatments. Leaf elongation was measured from day 0- 10 in the 7th leaf (a) and from day 15-25 in the 8th emergent leaf (b). Plants treated with 5mM did not produce an 8th leaf.

Our original hypothesis stated that meristematic extension growth would exhibit a greater degree of sensitivity to B toxicity than mature tissue. This hypothesis was tested in plants grown at B concentrations that occur in Californian conditions and found to be incorrect. Figure 2 illustrates the extension growth of the two youngest leaves over a 24 day period following application of the B treatments. Whereas clear visual symptoms of B toxicity occurred within 7 days of treatment with B concentrations of 0.5 mM or greater, and overall root and shoot biomass had been reduced by 14 days in all treatments of 0.5 mM or greater, there was no evidence of inhibition of extension growth or young leaf expansion in any plants treated with less than 5 mM boron. Treatment with 5 mM boron did result in a significant inhibition of leaf extension growth by day 10 (fig. 2) but only after very significant effects on whole plant growth and clear symptoms of toxicity had been observed. It is concluded that meristematic and extension growth is not inhibited by boron toxicity and that these tissues are not good indicators of plant boron status.

Additional experiments are now underway to define the stage of crop growth that is most sensitive to boron toxicity. These experiments will help determine when, during a crop growth season, a water source with high boron could most effectively be used for irrigation while still limiting crop damage.

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Salinity - Boron Interactions on Production and Forage Quality of Tall Wheatgrass (*Thinopyrum ponticum*, cv. 'Jose'): Implications on Ruminant Mineral Nutrition

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'Jose' tall wheatgrass was found to be extremely tolerant to boron even though some tissue samples exceeded 2,000 mg/kg dry weight. There was no significant salinity-boron interaction as found in other crops. Some mineral concerns related to ruminant nutrition are discussed.

Tall wheatgrass (*Thinopyrum ponticum*, cv. 'Jose') has been identified in a previous research project from the UC Salinity Drainage Program as a salt-tolerant forage that has high nutritional value and shows considerable promise for reducing saline drainage volumes in California's San Joaquin Valley (SJV). This drainage water also contains high concentrations of boron, Se and Mo, which may affect the production potential and mineral nutritional value of the forage. A greenhouse study was conducted on the UC Davis campus with soil-filled pots using irrigation waters that vary in boron (0.7 to 20 mg/L) and sodium-sulfate dominated salinity (0.5 to 20 dS/m), a quality characteristic of the SJV, with a constant background of 500 µg L Se and Mo. Our experiment confirms that Tall wheatgrass cv 'Jose' is very tolerant to salinity. For example forage production in treatments with irrigation water with an ECw of 10 dS/m (ECe of 16.8 dS/m) was 74% of those irrigated with non-saline water. We found that the stable carbon isotope fractionation served as good cumulative stress indicator of the crop as the discrimination value (Δ) decreased with increased salinity and reduced shoot biomass. Moreover, this forage crop is extremely tolerant to boron, tolerating up to 20 mg/L in the irrigation water without a significant reduction in cumulative biomass. Tissue boron concentrations increased with increased boron to values above 2,000 mg/kg dry wt. However as salinity increased within a particular boron treatment, tissue boron decreased.

The forage quality, from a ruminant mineral nutrition perspective, raised some concerns. Forage samples contained high levels of Se, Mo and sulfur near or above the recommended maximum tolerable concentrations. Therefore, ruminants consuming forage of this quality may have to be monitored for signs of Se accumulation in liver tissue, excess sulfur consumption and molybdenum-sulfur induced Cu deficiency. Nevertheless, forage of this quality has potential as a forage supplement.

Collaborative Efforts

Dr. Francisco Diaz is a visiting scientist from the Canary Islands whose salary was funded by a grant from the Spanish government.

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Evaluation of Wetland Adaptive Water Quality Management Strategies under a Real-Time Salinity TMDL

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This project has provided scientific support to a larger study of potential impacts to wetland moist soil plant habitat resulting from modification of seasonal wetland drawdown. Specific contributions have been the development of techniques for assessing wetland soil salinity using an electromagnetic sensing device and for developing accurate maps of moist soil plant habitat using high resolution multi-spectral imagery and image processing software.

This project has provided scientific support to a multi-year, interdisciplinary study of potential impacts to wetland moist soil plant habitat resulting from modification of the scheduling of seasonal wetland drawdown within the San Joaquin River Basin. Seasonal wetland drainage contributes salt loading to the San Joaquin River; changing the timing of these wetland contributions, if part of a comprehensive, basin-wide real-time water quality management system, can improve compliance with State salinity objectives and the current salinity TMDL. These wetlands are an important resource for over-wintering waterfowl and shorebirds on the Pacific Flyway, as well as for supporting the local economy through duck hunting and duck clubs.

This research project centers around six pairs of seasonal wetland ponds which range in size from 20 – 100 acres and were selected from State and privately managed wetlands within the 170,000 acre Grasslands Ecological Area. Each pair of matched sites allows traditional wetland drawdown management practices to be compared to those where drawdown is delayed until April 15 each year – with respect to impacts on water quality, wetland soils and moist soil plant habitat. The study aims to answer the question "How long can modified wetland management practices, designed to improve water quality in the San Joaquin River (SJR), be sustained without negatively impacting the biological value of waterfowl habitat?"

The following accomplishments have been made during the two year term of the project:

- The project team assisted in the deployment of 24 telemetered (radio and cellular modem) flow and water quality monitoring stations measuring continuous electrical conductivity, temperature, and stage at the inlet and outlet of the six paired wetland pond sites. Salt fluxes in and out of each pond were measured under both traditional and delayed drawdown schedules. The delayed schedule coincided with high SJR assimilative capacity (between April 15 and May 15 each year) associated with reservoir releases to aid fish migration.
- Three sets of high-resolution multi-spectral images were acquired for the study area (pre-treatment in 2006, and post-treatment 2007, 2008). The project team, with scientists at Berkeley National Laboratory, developed techniques using plant association-specific spectral signatures to identify 29 of the most important wetland plant associations. Of those, 9 were moist soil plant associations that included *Crypsis schoenoides* (swamp timothy), a dominant moist soil plant in the Grasslands Ecological Area. With the signatures, estimates of swamp timothy presence and absence were made across the study area.
- High resolution soil salinity maps were created using a Geonics electromagnetic field instrument (EM-38). Twelve soil samples per field were used for calibration.

- Stationary sensor arrays were deployed to measure wetland pond salinity. The arrays provided continuous monitoring of moist soil conditions in the wetlands from just before drawdown through drainage and the evaporative drying period. Resulting time series for soil parameters include temperature, salinity, and moisture. These results provide a temporal linkage between the spatial EM-38 mapping efforts.
- Methods have been developed for correlating reflectance spectra from aerial imagery with manual swamp timothy productivity survey data and are being applied to the 2008 data sets. These results are also being compared with the EM-based salinity maps, using salinity-moisture time series data to account for any significant time differences in the survey maps. The integrated results will enable us to provide significant input on how long modified wetland management practices, designed to improve water quality in the SJR, can be sustained without negatively impacting the biological value of waterfowl habitat.
- Supplemental funding was acquired through a California Department of Water Resources Prop. 204 grant (PI Quinn, co-PI Harmon) to develop mathematical models of seasonal wetland hydrology and to improve the representation of these wetlands in the current WARMF-SJR model.

Significant scientific outputs from the study include: (a) development of a robust monitoring system platform for measuring real-time flow and water quality data; (b) the finding that moist soil plant vegetation associations vary sufficiently between wildlife management areas and that spectral signatures need to be developed independently for each to achieve accurate representation. Initial classification was performed using e-Cognition software for image segmentation and ERDAS Imagine for classification. We developed a methodology whereby the analysis can all be done within the e-Cognition software. The team developed the first accurate map of major moist soil plant associations for the ponded areas which have provided the first quantification of temporal shifts in wetland plant habitat. (c) Soil salinity surveys revealed a likely mechanism of salt deposition within the wetland soil profile. This has allowed the protocol for sampling bulk soil salinity to be adapted – thus providing a more accurate assessment of soil salinity changes over time.

Publications

Quinn, N.W.T. Environmental decision support system development for seasonal wetland salt management in a river basin subjected to water quality regulation. *Agricultural Water Management*, in press.

Rahilly, Patrick J. (2008). M.S. Thesis: Investigating the Dynamics of Managed Wetland Ecosystems in the Grasslands Ecological Area. University of California, Merced.

Professional Presentations

Rahilly, Patrick, Ricardo Ortega, Nigel Quinn, and Thomas Harmon, New Tools for Ecological Impact Assessment in Managed Seasonal Wetlands (poster), CA Water and Environmental Modeling Forum 14th Annual Meeting, Monterey, CA, Feb. 26-28, 2008.

Harmon, Thomas, Designing Model-Driven Sensor Systems to Close the Loop on Water Resources Management in the West, University of Nevada Reno Fall Colloquium Series, Sept. 26, 2008 (invited).

Collaborative Efforts

This work is part of a larger collaborative effort between the co-investigators and the following agencies: John Beam, William Cook, Lara Sparks, and Ricardo Ortega, *California Department of Fish and Game*; Ernie Taylor and Joe Tapia, *California Department of Water Resources*; and Qinghua Guo, *University of California, Merced & Sierra Nevada Research Institute*.

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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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[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.

We have demonstrated that moderately saline water can be used as the primary irrigation source for Bermuda grass (*Cynodon dactylon* (L.) Pers) production in the western San Joaquin Valley. Forage yield and quality have been evaluated at a severely salt-affected site near Stratford, in Kings County, and at a greenhouse trial at UC Davis. Analyses of grass samples from selected sites with 7 (S1), 14 (S2) and 21 (S3) dS/m of ECe, and a fertilization of 0 (N0), 300 (N1) and 600 (N2) kg N/ha at Kings County and at UC Davis have shown a clear effect of salinity and N on the yield and quality of the forage. Figure 1 shows the total yield (cumulative biomass) in the pot trial under different salinity and nitrogen levels. The pots were irrigated with saline water (6 dS/m) three times a week during the 2007 growing season. At a low nitrogen level (without fertilization) the crop yields are low and the effect of salinity is not important. Pots with 7 and with 21 dS/m yielded close to 60 grams of dry matter (gr DM)/year. With a fertilization equivalent to 300 kg N/ha there is a clear effect of salinity on the cumulative biomass. Pots with 7 dS/m yielded 135.6 gr DM/year, while pots with 21 dS/m yielded only 82.8 gr DM/year. There is also a clear effect of salinity and nitrogen on the quality of the forage (proportion of leaves and stems). The leaf/stem ratio increases with fertilization, especially at the end of the growing season (see Figure 2). High salinity also increases the proportion of leaves at the end of the season. At 21 dS/m plants barely survive and the biomass is composed mostly by leaves and inflorescences, with almost no presence of stems. 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. During the 2008 growing season we have been adding 0.5 mg/L of Mo and Se, and 50 mg/L of B to the irrigation water at the greenhouse trial, and collecting forage samples every 30 days. This will allow for a systematic assessment of the capacity of Bermuda grass to accumulate these trace elements as a function of

Students taking forage samples at UC Davis.

salinity, fertilization 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.

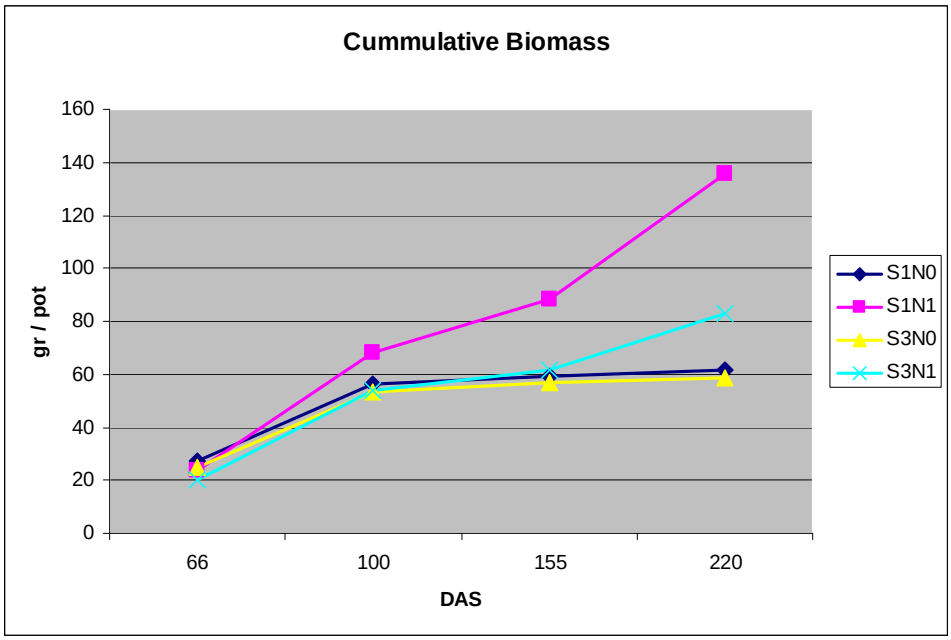

Figure 1. Forage yield at the greenhouse trial. DAS: Days after seeding

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.

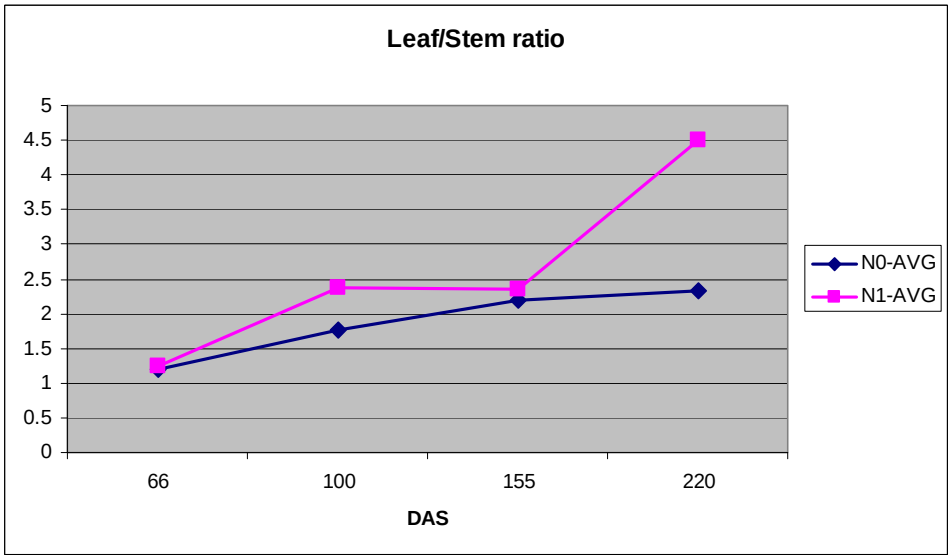

Figure 2. Leaf/stem ratio at different nitrogen levels

Alonso, Maximo and Stephen Kaffka, Bermuda grass as an alternative for retired farmland in the western San Joaquin Valley of California, Farming with Grass Conference, Soil and Water Conservation Society, Oklahoma City, OK, October 2008.

Collaborative Efforts

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Assessment of Seawater Intrusion Potential from Sea Level Rise in Coastal Aquifers of California

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The aim of this project is to develop a model of saltwater intrusion potential due to sea level rise for the next one hundred years on two groundwater basins in California – Seaside and Oxnard. FEFLOW finite element modeling software is used to render the three-dimensional hydrogeologic structure of each aquifer and to model the flow of groundwater and change in salt concentration over time.

One of the likely impacts of modern-age climate change in California identified by the California Department of Water Resources is the increased potential for salinity intrusion into coastal aquifers, where plausible estimates of sea level rise range from 0.10 to 0.90 meters. One effect of such an increase in sea-level is to induce seawater intrusion into the coastal aquifer. This project examines quantitatively the threat of sea-level rise in two of California's most productive coastal aquifers: the Oxnard Plain aquifer in Ventura County and the Salinas Valley coastal aquifer in Monterey County.

The objectives of the project are threefold. The first objective is to develop a method to rapidly assess the intrusion potential by utilizing the flow-net geometry of coastal groundwater flow. The second objective is to create numerical simulations of seawater intrusion for each aquifer using state of the art finite element modeling software. The third objective is to use these models to make recommendations to counter the probable impacts of sea-level rise.

The FEFLOW numerical model for the Seaside, CA area was completed in the first year. The 3D finite element model rests on a spatial definition of the relevant hydrogeology. In this case, the study area has three main water bearing structures (Santa Margarita Formation, Paso Robles Formation, and dune sand deposits) bounded by shale on the bottom. There is no barrier to flow between these units, and all share very similar hydraulic conductivity values.

The 3D model used an interpolation algorithm to model the bottom surface of the aquifer based on cross sections published in the literature as well as raw well log data in this and nearby aquifers. The topmost surface elevation layer was based on the highest resolution NED data.

Considerable effort was put into calibrating the model values of net inflow, storage, hydraulic conductivity, and initial values for head (i.e. pre-extraction water table) across the basin. Empirical reports and modeled values of hydraulic conductivity based in previous studies varied by an order of

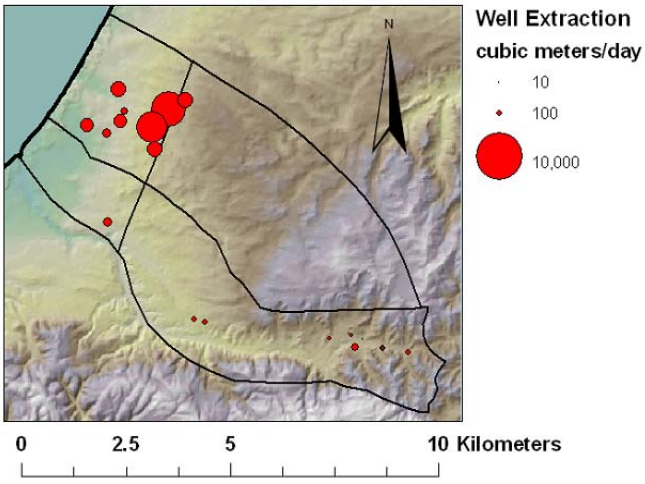

Figure 1. Study area and average annual groundwater extraction for 2002.

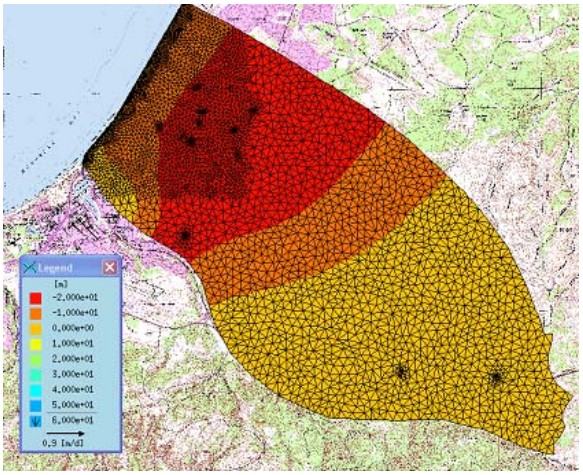

Figure 2. Simulated head for study area, 2106.

magnitude, and selection of a value that produced reasonable results when the model was applied over the recorded values for well extraction and head (1956-2002) was critical to producing a good estimate for water table drawdown, and thus seawater intrusion, for the next 100 years.

Simulations suggest that as water continues to be extracted at a faster rate than it is recharged a depression will continue to form in the northwest region of the aquifer, centered about 1.5 km from the coast. This depression will create a gradient that will result in an inflow of seawater, the front of which will reach major production wells for the area between 75 and 100 years from now.

Simulations using sea level increases of 0, 0.5 and 1.0 m over the next 100 years were run in the finite element model under the assumption of continued annual extraction equal to the year 2002 rate. These simulations suggest that while the effect of sea level rise is present, the principal driver of seawater intrusion into the Seaside aquifer is groundwater extraction.

Year two of the project will focus on constructing a model of groundwater flow and seawater intrusion potential for the Oxnard Plain.

Professional Presentations

Loáiciga, Hugo and T. Pingel, Assessment of seawater intrusion potential from sea level rise in coastal aquifers of California, Spatial@UCSB Opening Poster Display, Santa Barbara, CA, May 2008.

Collaborative Efforts

The poster presented at the Spatial@UCSB event allowed for contact between the second author and a group of graduate students attempting to assess the economic impacts of seawater intrusion in the Santa Barbara, CA area. We were able to assist this group in planning data discovery and methodologies to highlight potential risks in the area.

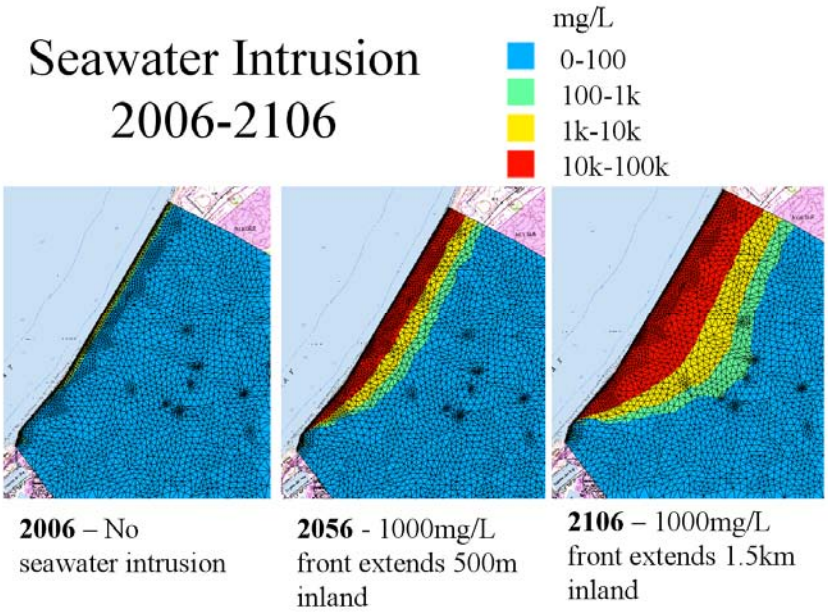

Figure 3. Modeled advancement of saline front, 2006-2106.

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Impacts of Delayed Drawdown on Aquatic Biota and Water Quality in Seasonally Managed Wetlands of the Grasslands Ecological Area

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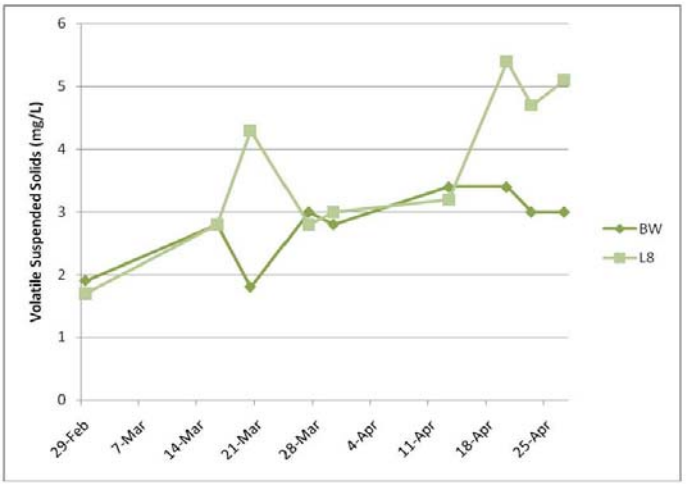
Compliance with water quality objectives may be improved by timing wetland drawdown to coincide with periods of high San Joaquin River assimilative capacity for salt. This project investigated some of the impacts of a delayed wetland drawdown on algae biomass and on water quality of seasonal wetland drainage. Delayed wetland drawdown is one of a number of management options for coordinating west-side San Joaquin Basin drainage salt loads with east-side reservoir releases that generate much of the River's assimilative capacity for salt. Experimental results of the current study show that algal biomass in the water column is most likely controlled by grazing zooplankton concentrations since no nutrient, insolation, or carbon limitations were observed. Algae concentrations dramatically increase during drawdown of wetlands due to the scouring of periphyton. Total and soluble nutrient concentrations were found to be low throughout the season. Nutrient concentrations increased during drawdown due to disturbance of nutrient rich sediments. Specific conductivity values rose in most wetlands throughout the season due to combined emergent plant evapotranspiration and direct pond evaporation. 79% of the VSS loading and 39% of the TDS load export occurred during drawdown. Turbidity had a strong correlation with volatile suspended solids concentrations. This correlation was seen in all wetland paired sites.

The 178,000-acre Grassland Ecological Area in California's San Joaquin Valley is managed to provide overwintering 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.

The experimental sites chosen were three pairs of matched wetland basins (20-100 acres each) that are part of the larger Modified Hydrology Study. For each wetland pair, one was managed with a traditional March drawdown; while the drawdown was delayed up to one month for the other to coincide with the period of high SJR assimilative capacity. Two additional drainage sites were added to the second year of sampling to better characterize drainage flowing to the SJR. Soil and water column samples were collected during the flooded periods at the inlets, outlets, and along transects within the wetlands. Water quality analyses included total/volatile suspended solids, conductivity, nitrogen (NH_4^+, NO_2^- +NO_3^-, organic), phosphorus (total, PO_4^{3-}), total organic carbon, alkalinity, turbidity, temperature, and pH. Planktonic and benthic



Phytoplankton concentrations at Buttonwillow Lake (BW) and Los Banos pond 38B (LB) drainage sites for the 2008 sampling season. Graph shows general increase over the season prior to and during wetland drawdown.

invertebrates were identified and enumerated.

Data were collected between February and April, 2007 and 2008. Identified phytoplankton were predominantly chlorophytes and diatoms. Zooplankton that feed on phytoplankton were found in abundance and consisted mostly of Daphinia. Benthic invertebrates were also assessed to help explain the differences in algal concentrations between ponds. Benthic invertebrates were found to be predominantly Chironomidae.

Seasonal loads of volatile suspended solids, total dissolved solids, and total organic carbon were estimated at the 2 drainage sites and at one modified hydraulic regime wetlands during the 2008 season. For volatile suspended solids the load was 1481 lbs, 2506 lbs, and 769 lbs respectively. For total dissolved solids the load was 553 lbs, 988 lbs, and 49 lbs respectively.

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 <9.0 pH). Sunlight intensity was not significantly attenuated by water depth or turbidity.

Total and soluble nutrient concentrations were low throughout the season. These levels increased during drawdown due to the scouring of nutrient rich sediments.

Specific conductivity values rose in most wetlands throughout the season due to moist soil plant evapotranspiration and direct pond evaporation. This was most noticeable in the Ducky Strike which were the shallowest of the wetland ponds surveyed.

Related Publications

Quinn N.W.T. Environmental decision support system development for seasonal wetland salt management in a river basin subjected to water quality regulation**.** *Agricultural Water Management*, in press. (Online 9/25/08)

Stringfellow W.T., J.S. Hanlon, S. E. Borglin, and N.W.T. Quinn. Sources of Biochemical Oxygen Demand in Western Tributaries of the San Joaquin River, California. *Agricultural Water Management*, 2008, 95(5): 527-538.

Professional Presentations

Quinn N.W.T., R. Ortega and L. Sparks. 2007. Sustainable adaptive management of brackish seasonal wetland habitat to meet salinity objectives in the San Joaquin River, California. Society of Wetland Scientists Annual Conference. June 10-15, 2007.

Collaborative Efforts

This project is part of a collaborative interagency effort to study water quality and ecological impacts of delayed drawdown in the Grassland Ecological Area. Contributors to our research include John Beam, Bill Cook, Lara Sparks, Ric Ortega and Charlotte Peters from the CA Department of Fish and Game, John Eadie from UC Davis, and Laura Castro and Ernie Taylor from the CA Department of Water Resources.

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Sustainable Eco-Systems under Land Retirement

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The analysis of data on the evolution of vadose zone salinity and perched water levels from Land Retirement Demonstration Project at Tranquillity site located in the Western Fresno County show that effective unsaturated soil hydraulic property change with average soil water salinity.

Use of intensive irrigation in arid and semi-arid areas usually leads to gradual salination of the soil, detrimental to crop-yields. The salination 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 of 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 agricultural activity. The abandoned land may even lead to desertification with adverse environmental 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 effect of the land retirement option 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

Retired land on the Westside of the San Joaquin Valley

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 investigated the processes of soil water and salinity movement in the root zone and the deep vadose zone. The simulation, covering a time span of 5 years, used measured perched water table depth and changes in the average root zone soil salinity as given by electrical conductivity measurements to optimize soil water retention properties, solute transport parameters and downward flux values at three locations of the Tranquillity site. A new paradigm changing "bottom up approach" to sustainable land management for drainage impaired land is proposed. With this new approach it is feasible to design a sustainable land use regimen for drainage impaired lands in general, and retired lands in particular. The analysis of data on the evolution of vadose zone salinity and perched water levels also show that effective unsaturated soil hydraulic properties change with average soil water salinity.

Professional Presentations

Singh, Purnendu and Wesley Wallender, Sustainable root zone salinity in the context of shallow perched water table, and attenuation: Land retirement demonstration project in the west San Joaquin Valley, California Central Valley Groundwater Modeling Workshop, Berkeley CA, July 10-11, 2008.

Wallender, Wesley and Purnendu Singh, Land Retirement: Root Zone Salinity in the context of shallow region groundwater conjunctive use and attenuation, University of California Salinity and Drainage Conference, Sacramento CA, March 26, 2008.

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

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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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Department of Land, Air and Water Resources
University of California Davis

Compared with a standard ranch practice of low density, fully irrigated trees, we reduced irrigation water use of mature almonds by 34% using regulated deficit irrigation (RDI) that imposed preharvest stress coupled with a high density planting with only a 3.6% decrease in yield.

The differential irrigation rates in the regulated deficit irrigation (RDI) regimes were successfully accomplished in 2008 and monitored with water meter measurements. Tree water deficits were quantified with weekly midday shaded leaf water potential measurements. Arrangements were made with the cooperator to modify fruit sampling at harvest that significantly reduced the manpower required during harvest. The cooperator was briefed on procedures to be used during the harvest to insure that we obtain accurate yield records. These included keeping close track of which truck-trailers come from the specific tree rows so they can be correlated with our plot locations. The cooperator agreed to assign a single field person to those rows that contained our plots and his sole responsibility was to record the trailer numbers.

The harvest was successful and we were able to accurately access fruit yields and fruit quality. These will be incorporated into the Final Report. We are gratified with the cooperation we received from our grower/ cooperator, Paramount Farming Company.

Professional Presentations

Goldhamer, David A., 2008. Using regulated deficit irrigation to increase almond production and water productivity. Paramount Farming Company ranch manager and irrigation scheduling personnel meeting. Bakersfield, CA.

Collaborative Efforts

This project has a sister project known as CARDIP (California Regulated Deficit Irrigation Program) that involves RDI work on both tree and vine crops and has other principal investigators: Mark Battany, San Luis Obispo Farm Adivsor; Terry Prichard, LAWR Water Management Specialist in San Joaquin County; and Ken Shackel, Professor, Dept. of Plant Science.

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

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Partial root zone drying treatments delivering 25% and 40% less water per irrigation than the well-watered control reduced the total amount of irrigation water applied to navel orange trees by 41% and 42%, respectively. Conventional irrigation treatments delivering 25% and 40% less water than the control reduced the amount of irrigation water applied relative to the control by 26% and 52%, respectively. All reduced irrigation treatments significantly reduced total kilograms and number of fruit per tree and the yield of commercially valuable large size fruit, but increased the sugar content and sugar to acid ratio of the fruit.

The California citrus industry produces "picture perfect" navel oranges for the fresh fruit market on 124,385 irrigated acres. The cost of irrigation water is a major expense associated with citrus production. Partial root zone drying (PRD) is an irrigation strategy designed to increase water-use efficiency in fruit tree crops to further reduce production costs. The method limits vegetative shoot growth in favor of crop development with the goal that neither the current nor return yield is negatively affected. 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 PRD to reduce the amount of water used in citrus production and, thus, increase grower net income. The specific objectives are to: (1) reduce annual water use in a commercial navel orange orchard using PRD irrigation rates 25% or 40% less than the well-watered control under conventional irrigation (CI); (2) compare PRD treatments with CI at reduced rates (CI-RR) of 25% and 40% less than the well-watered control and with the control; (3) determine the effect of PRD and CI-RR treatments on soil moisture content on each side of the tree to schedule irrigation of the dry side and withhold water from the wet side of PRD trees or both sides of the CI-RR trees; (4) determine the effect of PRD and CI-RR treatments on total yield, fruit size and quality at harvest and return bloom for two crop-years; (5) provide initial soil moisture content values and number of calendar days for scheduling irrigation for PRD or CI-RR; and (6) provide a cost:benefit analysis of the results.

The design is a randomized complete block with five irrigation treatments and five replications of each in a commercial navel orchard at the University of California, Riverside Citrus Research Center and Agricultural Experiment Station. The treatments are: (1) well-watered control (based on evaporative demand); (2) 75% PRD and (3) 60% PRD – trees have an emitter on each side, which alternate in delivery to one side of the tree, then the other; (4) 75% CI-RR and (5) 60% CI-RR – trees have an emitter on each side so that both sides of the tree are wet. Soil moisture content is measured on each side of a data tree in each treatment for two replications. Irrigation frequency is based on soil moisture content.

From 30 July 2007 to harvest 16 January 2008, 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 42%, respectively. Conventional irrigation treatments delivering 25% and 40% less water than the control reduced the amount of irrigation water applied relative to the control by 26% and 52%, respectively. All reduced irrigation treatments significantly reduced total kilograms and number of fruit per tree (Fig.1) and also the yield of commercially valuable large size fruit as both Kg and number of fruit per tree (Fig. 2).

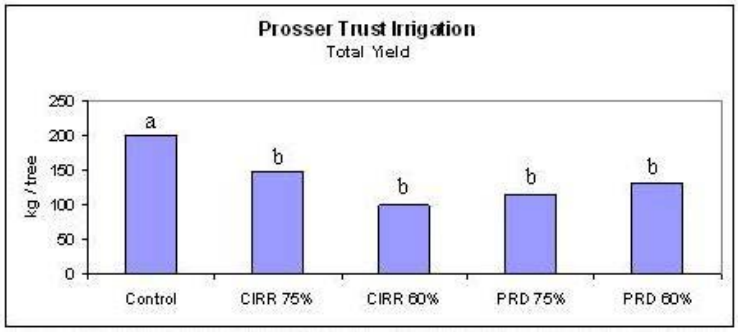

Fig. 1. Effect of reduced irrigation (75% and 60% of the well-watered control) by CI or PRD on yield (kg fruit/tree).

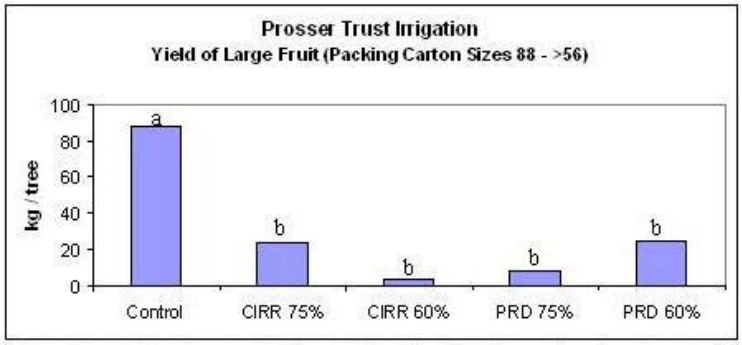

Fig. 2. Effect of reduced irrigation (75% and 60% of the well-watered control) by CI or PRD on yield (kg fruit/tree) of commercially valuable large size fruit.

With regard to fruit quality, all reduced irrigation treatments reduced the fresh weight of individual fruit by only 4%-10%, which corresponded to the 0%-10% decrease in total juice weight per fruit. No irrigation treatment had an effect on the juice volume of the fruit. All reduced irrigation treatments significantly increased the sugar and acid concentrations and sugar to acid ratio of the juice compared to fruit from well-watered control trees.

In year 1, the reduced irrigation treatments were initiated on 30 July, after the June drop period and during Stage II fruit development (growth dominated by cell expansion) to test the effect of reduced irrigation on fruit size independent of an effect on fruit retention. All reduced irrigation treatments had a significant negative effect on fruit size. Especially noteworthy was that even the CI-75% treatment reduced the yield of commercially large size fruit to the same degree as trees in the PRD 60% treatment. It was a surprise that reducing irrigation during such a late stage in fruit development had such a significant and negative impact on fruit retention.

For the remainder of the year from 16 January to 30 June 2008, trees in the CI-75% and 60% treatments received 25% and 61% less water than the control trees, respectively; whereas trees in the PRD-75% and 60% treatments received 55% and 61% less, respectively. We determined the effect of each treatment on the number and length of vegetative shoots comprising the summer shoot flush. These shoots are important as they can contribute > 70% of next spring's flowers. Trees in the PRD-60% irrigation treatment produced significantly more vegetative shoots per branch than trees in all other irrigation treatments. Since shoot length was not affected by irrigation treatment, trees in the PRD-60% treatment should flower more intensely in spring than trees in other treatments.

Professional Presentations

The project (without data) was presented at Huazhong Agricultural University, Wuhan, PR China, and Hunan Agricultural University, Changsha, PR China in August 2007.

Collaborative Efforts

Contributions of the UC Riverside Agricultural Operations staff continue to be very important. They check the orchard when buffer trees are being irrigated to make sure that there are no breaks in the lines that might result in our data trees receiving water they should not. They also take care of the nutrition and pest management for our trees.

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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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University of California, Los Angeles

The amount of water used in 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 in agriculture in California consumes 40% of the total water supply and 75% of the municipal and industrial 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 this 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.

In the first year of the project our work 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.

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

During the second year of the project, we developed the data assimilation framework by coupling the crop and radiative transfer models within the EnKF code. With this tool we performed observing system simulation experiments (OSSEs) to test the feasibility of estimating the soil moisture and vegetation states from readily available remote sensing measurements. Our preliminary results indicate that there may in fact be enough information in the multi-spectral measurements, when assimilated in the crop model, to estimate the soil and vegetation state. This is an encouraging finding in that knowledge of these states could be used to inform irrigation practices in real-time. Ongoing work involves testing the estimation system with real data taken from Oxnard, CA and the Imperial Valley.

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Coupling Automated Overhead, Low-pressure Irrigation Systems with Conservation Tillage: A New Irrigation, Crop and Drainage Management Paradigm for the Central San Joaquin Valley?

Jeff Mitchell
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University of California Kearney Agricultural Center

The project team is evaluating the potential of merging overhead, low-pressure irrigation systems with various conservation tillage practices as a means to reduce water use, save money, and increase farm profitability in California's San Joaquin Valley.

In this project, a team of several University of California researchers and extension advisors and private sector partners are evaluating the potential of merging overhead, low-pressure irrigation systems (center pivot and linear move) with various conservation tillage crop production practices as a means of reducing water use, saving money, and increasing farm profitability in the Central San Joaquin Valley. An 8-acre replicated field study has been initiated at the UC West Side Research and Extension Center in Five Points, CA to evaluate the performance of five irrigation / tillage systems in half-acre plots. The project field was cropped to wheat in the 2007 – 2008 winter, followed by a grain corn crop in 2008. This sequence will be repeated in 2008 – 2009. Irrigation application, soil water storage, crop growth, soil property, and yield data have been collected for the first cycle of this study and these data are currently being analyzed.

We are working closely with two San Joaquin Valley farmers, John Diener and Scott Schmidt, on this project and are also monitoring water application, soil water storage and crop performance at one of their center pivot fields.

To date, we have worked with the private sector supplier of the overhead irrigation system we are using to refine our management and to become familiar with optimal irrigation scheduling of this system. This refinement is being done in order to take full advantage of the system and to avoid surface ponding that we noticed to some extent in our first year. We now believe that we have the capability to avoid this and to improve our management as this project proceeds.

Because of the potential significance of the merging of overhead irrigation and no-till production technologies for California's Central Valley, we are submitting additional proposals to augment the work initiated in this project and are also making a request to have a companion study field at the West Side Research and Extension Center.

Overhead no-till project field
Fall 2007
Wheat

Professional Presentations

Mitchell, J.P. and D.S. Munk. Overhead irrigation and no-till production systems. 2008 Cotton Cropping Systems Annual Field Day. University of California West Side Research and Extension Center, Five Points, CA. September 17, 2008

Collaborative Efforts

A significant team has been coalesced to implement this study, including several UC scientists and extension education personnel, USDA NRCS conservationists, as well as a number of farmers, and other private sector participants. Many of these people routinely take part in our project discussion and planning meetings. This Water Resources Center-sponsored project has enabled a very significant collaboration and extension education effort that we believe will have considerable impact in coming years.

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

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[3]USDA-ARS George E. Brown, Jr. Salinity Laboratory

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.

Earlier studies: 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.

Experimental / Field setup: 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 or 2008 as the grower stopped all his Westside cotton production due to severe shortage of canal water.

Plant / yield data: Plant tissue analysis showed a significant 0.5 to 3 fold increase in chloride and boron levels in both cotton and pistachio tissues, 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 under saline irrigation 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. But lint yield from the saline Well treatment was reduced by 275 lb/ac compared to the Aqueduct water. However, the Well treatment yield was still excellent at 3.12 bale/ac. Increase in pistachio rootstock di-

ameter and general tree development was unaffected by salinity after three years. By the end of the fourth year the PG1 rootstock diameter in the Well treatment was reduced by 7% compared to the Aqueduct treatment (P=0.04). The UCB rootstock was not affected by salinity.

Salinity and sustainability: At the end of 2006, after three seasons of cotton irrigation this program has applied about 6600, 32500 and 54000 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 can be as high as 11 dS/m. Without 6 to 10 inches of effective rainfall or fresh water winter irrigation for efficient leaching this system may not be sustainable. Due to the decrease in cotton yield in 2006, combined with a 50% increase in the Well water EC over the last four years, we reduced the salinity of the Well treatment (by blending with Aqueduct water) down to 4.5 dS/m starting July 2007. This is about the salinity of the Well treatment at the start of the test in 2004. Even with the decreased lint yield for the Well treatment in 2006, an economic analysis of cotton yield return to the project shows a net return of $2,249/ac using the $45/ac-ft Well water compared to $2,120/ac for the $120/ac-ft Aqueduct water. But after five years the Well water adds 73,800 lb/ac salt in the wetted zone of the pistachios compared to about 8,000 lb/ac for the Aqueduct water.

Publications

Sanden, B.L., L. Ferguson, C. Kallsen, D. Corwin. 2007. Large-Scale Utilization of Saline Groundwater for Development and Irrigation of Pistachios (P. integerrima) Interplanted with Cotton (G. barbadense) Proceedings of the Vth International Symposium on Irrigation of Horticultural Crops, Eds: I. Goodwin and M.G. O'Connel, Acta Horticulturae, ISHS 792:551-558.

Sanden, B., L. Ferguson, C. Kallsen, D. Corwin, B. Marsh, B. Hutmacher. 2007. Using saline groundwater for large-scale development and irrigation of pistachios interplanted with cotton. Proceedings 28th Annual International Irrigation Show, 12/9-11/07, San Diego, CA. Irrigation Assoc. 6540 Arlington Blvd, Falls Church, VA 22042. pp.779-785

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Collaborative Efforts

USDA Salinity Lab, Riverside, CA: Dennis Corwin – Aerial and ground GIS data analysis. Patrick Taber, Don Suarez – modeling rootzone salinity.

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