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# Table of Contents

## RESEARCH PROJECT INDEX

### Research Category I – Hydrology, Climatology and Hydraulics

Project Title	Principal Investigator	Location	Page
<i>Joint Inversion of Groundwater Flow and Environmental Tracer Data for Aquifer Characterization</i>	Timothy Ginn	UC Davis	2
<i>Simulating and Understanding Variability in Runoff from the Sierra Nevada</i>	Alex Hall	UC Los Angeles	5
<i>Predicting the Impacts of Urbanization on Basin-scale Runoff and Infiltration in Semi-arid Regions</i>	Terri S. Hogue	UC Los Angeles	7
<i>High Resolution Modeling of Flood Inundation</i>	Brett F. Sanders	UC Irvine	9

### Research Category II – Aquatic Ecosystems

<i>Climate Variability of the Sierra Nevada over the last Millennium: Reconstructions from Annually Laminated Sediments in Swamp Lake, Yosemite National Park, California</i>	Daniel R. Cayan	Scripps Institution of Oceanography	12
<i>Control of Mercury Methylation in Wetlands through Iron Addition</i>	David L. Sedlak	UC Berkeley	14
<i>Restoring Rangeland Watersheds and Fisheries: Pine Creek Watershed and Eagle Lake Rainbow Trout</i>	Lisa C. Thompson	UC Davis	16

### Research Category III – Water Quality

<i>The Effects of Current-use, Sediment-bound Pesticides on a Coastal Marine System</i>	Donald P. Weston	UC Berkeley	19
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**Research Category IV – Water Development and Management Alternatives**

No current projects in this category

**Research Category V – Water Law, Institutions and Policy**

<b>Project Title</b>	<b>Principal Investigator</b>	<b>Location</b>	<b>Page</b>
<i>Securing Access to Water: Institutional Strategies for Coping with Drought and Water Scarcity</i>	Ronnie D. Lipschutz	UC Santa Cruz	<b>22</b>
<i>Integrated Regional Water Management Planning in California: Developing Institutions for Collective Action</i>	Mark Lubell	UC Davis	<b>25</b>
<b><u>Special Projects</u></b>			
<i>Maintenance and Dissemination of a Water Transfer Data Base</i>	Gary D. Libecap	UC Santa Barbara	<b>28</b>
<b><u>Salinity/Drainage Program</u></b>			
<i>Application of Redox Mediators to Accelerate Removal of Selenium from Agricultural Drainage Water</i>	Christopher Amrhein	UC Riverside	<b>30</b>
<i>Prototyping and testing of a Lagrangian sensor network for distributed monitoring in the San Joaquin - Sacramento Delta</i>	Alexandre Bayen	UC Berkeley	<b>31</b>
<i>Mechanisms of Boron Toxicity in Crop Plants</i>	Patrick Brown	UC Davis	<b>33</b>
<i>Bermuda Grass Yield and Quality in Response to Different Salinity and N, Se, Mo, and B Rates in West San Joaquin Valley</i>	Stephen Kaffka	UC Davis	<b>35</b>
<i>Assessment of Seawater Intrusion Potential from Sea Level Rise in Coastal Aquifers of California</i>	Hugo A. Loáiciga	UC Santa Barbara	<b>37</b>
<i>Impacts of Delayed Drawdown on Aquatic Biota and Water Quality in Seasonal Wetlands</i>	Nigel W. T. Quinn	UC Merced	<b>39</b>
<i>Sustainable Ecosystems under Land Retirement</i>	Wesley W. Wallender	UC Davis	<b>41</b>

**Irrigation Management Program – Prosser Trust**

<b>Project Title</b>	<b>Principal Investigator</b>	<b>Location</b>	<b>Page</b>
<i>Assessing Orchard and Vineyard Irrigation Needs with Thermal Imagery</i>	David A. Goldhamer	UC Davis Kearney Agricultural Center	<b>44</b>
<i>UC Irrigation Water Management Web-based Research and Information Center (IrRIC)</i>	Stephen Grattan	UC Davis	<b>46</b>
<i>Reducing Water Use in Navel Orange Production with Partial Root Zone Drying</i>	Carol J. Lovatt	UC Riverside	<b>48</b>
<i>Toward Improved Irrigation Efficiency through Real-time Assimilation of Multi-spectral Satellite Remote Sensing Data into Crop Models</i>	Steven A. Margulis	UC Los Angeles	<b>51</b>
<i>Coupling Automated Overhead, Low-pressure Irrigation Systems with Conservation Tillage: A New Irrigation, Crop and Drainage Management Paradigm for the Central San Joaquin Valley?</i>	Jeff Mitchell	UC Davis Kearney Agricultural Center	<b>53</b>
<i>Development and Application of the Coupled Vadose Zone-Ground Water Flow Modeling Environment: HYDRUS Package for MODFLOW</i>	Jiri Šimůnek	UC Riverside	<b>55</b>
<b>PRINCIPAL INVESTIGATOR INDEX</b>			<b>57</b>



## 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.





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

Timothy R. Ginn, Hanieh Haeri, Laura Foglia  
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*Incorporation of different types of data such as piezometric head, solute or other tracer concentration, and age inferred from environmental isotopic data can improve parameter estimation and reduce non-uniqueness of inverse modeling-based calibration of groundwater models. We are interested to investigate the importance of the groundwater age observation in the inverse modeling and the extent of information it can provide to the inverse process in order to reduce its inherent non-uniqueness in a real world aquifer.*

Most groundwater flow models have been calibrated using only hydraulic head measurements as complementary data to whatever geologic information is available. Model insensitivity and non-uniqueness often occur when head measurements are used alone. In many groundwater flow models, simulated heads are not highly sensitive to minor differences in the transmissive properties of the medium. This non-uniqueness in calibrated parameters brings into question the robustness of assigned values and the spatial distributions of hydraulic parameters. Of particular concern is the dependability of such a calibrated model under a new and different set of boundary conditions. Such insensitivity and non-uniqueness can be reduced by use of additional information gained from field observations of other types, for instance, flow rate at head-dependent boundaries, temperature, electrical resistivity, and tracer solute concentration. Incorporation of different types of data such as age, environmental isotopic data, temperature and other sources of information may dramatically improve the stability of inversion and the robustness as well as the reliability of the model. As noted by Anderman et al. (1996), advective-dispersive transport observations reflect groundwater velocities and patterns over a long period of time and provide more complete information about the groundwater flow system than flow measurements taken at a discrete point in time.

In our preliminary idealized study we applied modeling of both flow and transport in an idealized 2-D problem in the forward sense to solve simultaneously the steady-state piezometric head and mean age distributions, the output of which is used as input to an indirect inversion scheme to calibrate some of the parameters involved. The goal of this study was to understand how addition of observation data density and type (e.g., head, flow rate, age) can improve the inverse solution and potentially reduce its inherent non-uniqueness. Based on the results of our study, the addition of groundwater age data was found to reduce the level of non-uniqueness as defined by the mean square error between the estimated hydraulic conductivity field and the true field (taken here as a measure of non-uniqueness) in our parameter estimation. The implication is that for inverse calibration of hydraulic condition age, that reflects advective-dispersive transport, may serve as a more powerful data type than head, which reflects local conditions through the diffusion operator. Nevertheless, the non-uniqueness persists because the heterogeneity of the domain allows different flow-fields to generate similar mean ages at the observation locations. This reflects that the global nature of age does not guarantee uniqueness, as long as data are absent from locations where observations are needed to distinguish paths that give rise subsequently to similar ages at downstream locations,

even when ages depart upstream. One potential way to address remaining non-uniqueness is to collect age data at observation locations at multiple points along the flow paths. For instance, with addition of some samples at the bottom of a two-dimensional (section view) aquifer, the calibration resulted in unique solutions in our idealized study. These simple results reflect that distributed sampling location and combined use of different calibration targets (such as head and age) help to partially overcome the intrinsic non-uniqueness of the inverse problem.

In another part of our study we simulated the entire distribution of groundwater age under both transient and steady-state conditions in another idealized setting. Unlike the “tracer concentration measurement” which yields a single-valued estimation of age of water at a particular location, a water sample represents a mixture of different ages as a result of waters travelling in different flow-paths. Even the use of higher moments besides the mean of groundwater age may not adequately describe the important age densities represented in a given sample because the shape of underlying distribution is generally unknown. This may lead to possible misinterpretations of natural travel time and consequent errors in estimating the values of hydraulic parameters that are related to travel time. To investigate the impact of aquitard-aquifer mass transfer on groundwater age, we seek to examine the form of the distribution of groundwater age in such an idealized setting and how it changes with time. We used a synthetic system that consists of two layers of aquifers adjacent to an aquitard following Bethke and Johnson (2002) and simulated both the entire distribution of groundwater age and the mean groundwater age in both transient and steady-state conditions. The results showed that for even idealized heterogeneous aquifers, the distribution of groundwater age does not reach steady-state for relatively long times after perturbations in boundary fluxes. This result brings into question the validity of the steady-state assumption when applied to groundwater

age in natural subsurface materials. It also highlights that age distributions can be expected to change gradually with trending changes in driving fluxes (e.g., climate change) and are not currently, or for the foreseeable future, at steady state.

As the next step of our study we choose a regional alluvial aquifer system in the San Joaquin Valley, surrounding the Modesto city area dominated by irrigated agriculture to investigate the importance of the groundwater age observation in the inverse modeling and the extent of information it can provide to the inverse process in order to reduce its inherent non-uniqueness in a real world aquifer. The boundaries of the regional groundwater system are the Merced River at the south, the Sierra Foothills at the east, the San Joaquin River at the west, and the Stanislaus River at the North. The San Joaquin Valley aquifer has been modeled by USGS (Phillips et al., 2007) and the model was provided to us. Our goal is to collect piezometric head, concentration, and environmental isotopic data so that we can evaluate the relative value of combined head, concentration and groundwater age data (as opposed to only head data) in the quality of the inversion and estimated parameters for this regional groundwater flow model. As was shown in our preliminary idealized study it is necessary to have age dating observations of both deep and shallow aquifers so that we can capture all the information provided by the advective-dispersive transport in the system. Thus another goal of our study is to evaluate the relative importance of the observation locations in the parameter estimation quality, this would help us to determine where additional observation should be added. Also, as typically several types of age dating data are available in this basin, another goal of the study is to evaluate relative importance of the different environmental isotopic data at different depths of the aquifers in parameter estimation quality.

To summarize, our preliminary idealized studies showed that incorporation of different types of data such as piezometric head and age data can improve parameter estimation

and reduce non-uniqueness of inverse modeling, and that steady-state assumptions about the distribution of groundwater age (and therefore also its moments) are not generally applicable. To investigate these aspects in a realistic setting we choose a regional alluvial aquifer system in the San Joaquin Valley, California. We are using the USGS San Joaquin Valley regional model (Phillips et al., 2007) and have done some modifications on the model, including the refinement of the grid at the city of Modesto (local model) using the refinement capability of MODFLOW (MODFLOW\_LGR, Mehl and Hill, 2005). We are building a coupled transport model via MODPATH to simulate the groundwater age and configuring the model for inversion using both piezometric head and groundwater age data via UCODE. This will allow us to explore the linkages between the three models: (1) flow model via MODFLOW-LGR, (2) transport model via MODPATH and (3) inverse model via UCODE.

### **Publications**

Ginn, TR; Haeri, H; Massoudieh, A, Foglia, L. Notes on Groundwater Age in Forward and Inverse Modeling, TRANSPORT IN POROUS MEDIA, 2009, 79 (1): 117-134.

### **Professional Presentations**

Haeri H., Foglia L., Ginn TR., Simulation of the Entire Distribution of Groundwater Age, American Geophysical Union (AGU), San Francisco, December 2008.

Haeri H., Foglia L., Ginn TR., Downscaling from Regional to Local Scales in Groundwater Flow Modeling, 27th Biennial Groundwater Conference, 18th Annual Meeting of the Groundwater Resources Association of California, Sacramento, Oct 2009.

### **Collaborative Efforts**

As part of this study, the city of Modesto asked us to characterize the groundwater hydraulics in the vicinity of six selected rockwells installed in the city, and to use this information to plan the locations of observation wells to be installed near the rockwells, one upgradient and one downgradient per each selected rockwell.

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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; 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 0.4°C per decade. Statistical analysis shows that the trend in snow mass peak timing can be explained by its sensitivity to local March temperatures. The snow mass peak timing is shown to shift earlier in the season by 1.3 days per 1°C 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

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-21<sup>st</sup> 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. Though the likelihood of snow melting is greater in the warmer climate, 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.

We are also actively working to improve simulations of hydrologic processes in regional climate models. We have undertaken a 12 km resolution simulation of the current climate of entire state of California, with higher resolution nests of up to 4km in the

hydrologically-critical region of the Sierras. We found that increasing model resolution significantly improves the realism of the precipitation and snowpack distributions in the Sierras. However, through comparison with streamflow observations in undisturbed watershed in the High Sierras, we also determined that the model melts water too early in the spring season. The reason for this has been traced to a bias in the model's handling of the amount of sunshine reflected by snow-covered surfaces. We are working to correct this bias, and anticipate producing a much more realistic simulation of the current and future behavior of the Sierra snowpack. The improved model and the accompanying observational snow data sets we've developed will be invaluable resources for prediction and understanding of water resources in California.

### **Publications**

Kapnick S, Hall A (2009) Observed climate-snowpack relationships in California and their implications for the future. Accepted to Journal of Climate.

Kapnick S, Hall A (2009) Observed Changes in the Sierra Nevada Snowpack: Potential Causes and Concerns. Submitted for publication in the 2009 Climate Action Team Report to the Governor and Legislature.

Kim, J, Fovell, R, Hall, A, Kapnick, S, Li, Q, Liou, K N, McWilliams, J, Qu, X, Xue, Y, Chao, Y, Eldering, A, Friedl, R, Waliser, D (2009) A Projection of the Cold Season Hydroclimate in California in Mid-Twenty-First Century Under the SRES-A1B Emission Scenario. Submitted for publication in the 2009 Climate Action Team Report to the Governor and Legislature.

### **Professional Presentations**

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

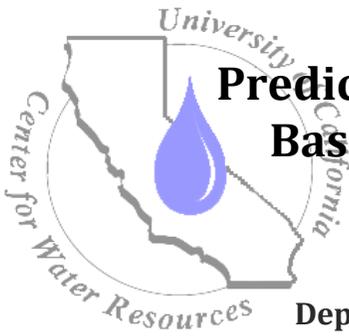
Kapnick, Sarah, Observed Climate-Snowpack Relationships in California and Their Implications for the Future (poster), Sacramento, CA, September 2008.

### **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. The goal of the current study is to develop a coupled modeling and urban growth planning framework for guiding the efforts involved in regional urban development planning and water supply management.*

Semi-arid environments are generally more sensitive to urbanization than humid regions in terms of both hydrologic modifications and water resources sustainability. The current study integrates hydrologic modeling and land use projections to predict long-term impacts of urbanization on hydrologic behavior and water supply in semi-arid regions. This project focuses on the Upper Santa Clara River basin in northern Los Angeles County, California, which is undergoing rapid and extensive development. The semi-distributed Hydrologic Simulation Program-Fortran (HSPF) model is parameterized with land use, soil, and channel characteristics of the study watershed. Model parameters related to hydrologic processes are calibrated at the daily time step using various spatial configurations of precipitation and model parameters. Potential urbanization scenarios are generated on the basis of a regional development plan. The calibrated (and validated) model is run under the proposed development scenarios for a 10 year period. 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 ex-

pansion 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 selected as the primary study area. The 640 mi<sup>2</sup> 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 Clara-Valencia corridor. The Santa Clara watershed supports a series of groundwater basins within the floodplain regions along the river. The selected study area comprises two primary groundwater basins, the Acton Valley Basin (12.9 mi<sup>2</sup>) and the SCR Valley Basin (103 mi<sup>2</sup>). 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. The estimated changes in recharge for potential development in the upper Santa Clara River watershed (USCRW), although relatively small in absolute numbers, equate to significant loss in recharge volume for the developing area. Sub-basin four in the USCRW, where the proposed development is focused, is approximately 217 km<sup>2</sup>. A decline in recharge of 0.67 mm over the proposed basin (from aggregated model output) results in a volume loss of 0.145 Mm<sup>3</sup>/year (primarily during the wet season). Given the current per capita water use in southern California (~185 gal/day (0.7 m<sup>3</sup>/day); MWD, 2005), the recharge

volume loss equates to a supply for around 600 people each year on average. For the extreme case (S4), the decrease in recharge of 3.96 mm across the sub-basin results in an estimated loss of 0.859 Mm<sup>3</sup>/year, or enough water to supply approximately 3400 people each year. Although the estimate of recharge loss from the S4 case is more extreme and includes significantly more uncertainty than estimates for the proposed level of development under S1, the case is presented to illustrate the potential impacts of cumulative, long-term development on watershed function and recharge loss.

### **Professional Presentations**

Improving Global Optimization of Hydrologic Models, Institute for Pure and Applied Mathematics (IPAM) Workshop on Transport Systems in Geography, Geosciences and Networks, UCLA, May 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 inundation modeling by tailoring multi-dimensional flood inundation models to increasingly available high-resolution geospatial datasets including LiDAR DEMs, aerial imagery and many other datasets characterizing urban landscape features.*

## RESEARCH MOTIVATION AND OVERVIEW

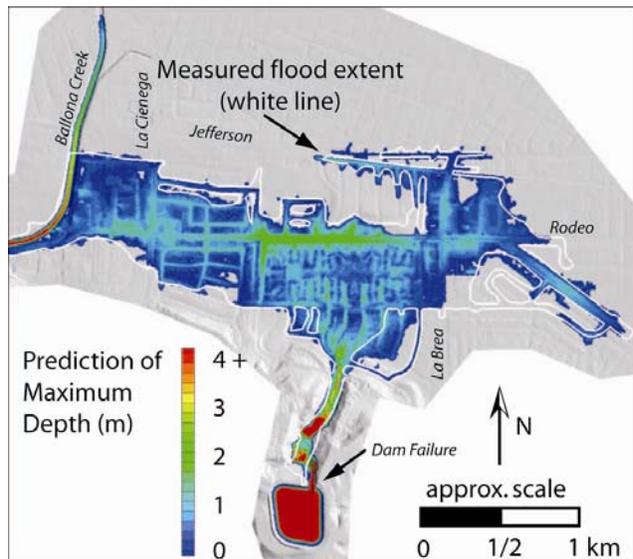
Government at all levels is increasingly investing in Geographical Information Systems (GIS) to archive, access and regularly utilize a wide range of important data resources. These data are particularly rich in urban areas due to the density of infrastructure, and data characterize a vast array of features ranging from parcel boundaries and building footprints, land cover attributes, critical lifeline infrastructure and census data, to name just a few. Flood risk management efforts increasingly rely upon 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 the 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. Research led by Professor Sanders at UC Irvine is aiming to advance a new generation of high-resolution, multi-dimensional flood inundation models that leverage the data resources described above and build upon fundamental advances made in the computational sciences over the past decade. The goal of this research is to enable decision makers to better understand and predict the consequences of flooding, and to do with greater speed, frequency and

precision than is possible with today's modeling technology.

Funding this year supported a modeling study of the Baldwin Hills dam-break flood, which occurred in Los Angeles in December, 1963.

## BALDWIN HILLS STUDY

The Baldwin Hills reservoir was placed into service in April, 1951 to support water supply and distribution in the southwestern portion of Los Angeles. Situated over the Newport-Inglewood Fault, the reservoir was constructed of flexible earthen materials including an extensive drainage system in anticipation of settlement and seepage. Unfortunately, surface faulting directly under the reservoir compromised the integrity of the system. Under high pressure, channelized flow through the fault eroded and expanded the



fill material below the reservoir and ultimately breached the dam. The resulting flood caused extensive damage downstream including destruction of homes, apartment buildings, roads and flood control infrastructure. The surface faulting that caused failure was later attributed to regional subsurface fluid injection associated with oil recovery and waste disposal activities.

This study focuses on the predictability of dam-break flooding in highly urbanized and relatively flat terrain, as is found below the Baldwin Hills reservoir. The highly urbanized Los Angeles basin, like many developed areas, is surrounded by dozens of reservoirs; and dam operators must plan for the possibility of failure using model predictions of flood extent and flood arrival times. Advances in computational models and improvements in terrain mapping offer the potential for improved predictions.

Here, a two-dimensional overland flow model is coupled to a model for sub-surface sewer flows and applied to the study site to predict flood inundation. Various aspects of the modeling approach including the terrain data resolution, the resistance parameter distribution, the magnitude of sewer flows, and the dam beach configuration are considered relative to the overall accuracy of the model.

To support this project, high resolution Light Detection and Ranging (LiDAR) terrain data and orthoimagery were obtained from the Los Angeles Region – Imagery Acquisition Consortium (LAR-IAC). In addition, flood extent data and Ballona Creek stream flow data were obtained for model validation purposes.

The results of this study show that urban flooding can be predicted on a street by street basis if a robust numerical flow solver is used and parameterized with high-resolution terrain data that depicts the detailed topography of urban landscapes. In particular, streets may be depressed relative to neighboring parcels and it is imperative that street flows be resolved by at least three computational cells for flood extent and stream flow accuracy. Results also show that sewer flows are important relative to flood

extent and should be modeled. Results show that resistance parameters have relatively little effect on flood extent, but are important relative to arrival time predictions.

The broader implication of this study is that dam owners and emergency response agencies would be well served to revisit the modeling studies that support dam-safety plans (e.g., evaluation zones and warning times) to obtain more realistic flood predictions. Existing safety plans are likely based on simplistic inundation models and relatively crude data such as 10 m resolution (7 m vertical accuracy), National Elevation Data (NED). In this study, use of NED caused a significant over-prediction of flood extent. A full account of this study appears in Gallegos et al. (2009).

### **Publications**

Gallegos, H.A, Schubert, J.E. and Sanders, B.F. Two-dimensional, high-resolution modeling of urban dam-break flooding: A case study of Baldwin Hills, California. *Advances in Water Resources* 2009, 32, 1323-1335.

### **Professional Presentations**

Sanders, B.F. Hydrodynamic routing of flood inundation over urban landscapes: Effective utilization of geospatial data and efforts to improve run-time efficiency, *Fluid Mechanics and Hydrology Seminar Series*, Department of Civil and Environmental Engineering, UC Berkeley, November 7, 2008.

Sanders, B.F. High resolution modeling of urban dam-break flooding: A case study of Baldwin Hills, California, *Los Angeles County Department of Public Works*, June 16, 2009.

High resolution modeling of flood inundation, *Noblis*, Falls Church, VA, June 23, 2009.

Improved Flood Inundation Modeling with LAR-IAC LiDAR Data and Orthoimagery, *Los Angeles Region Imagery Acquisition Consortium (LAR-IAC)*, July 30, 2009.

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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

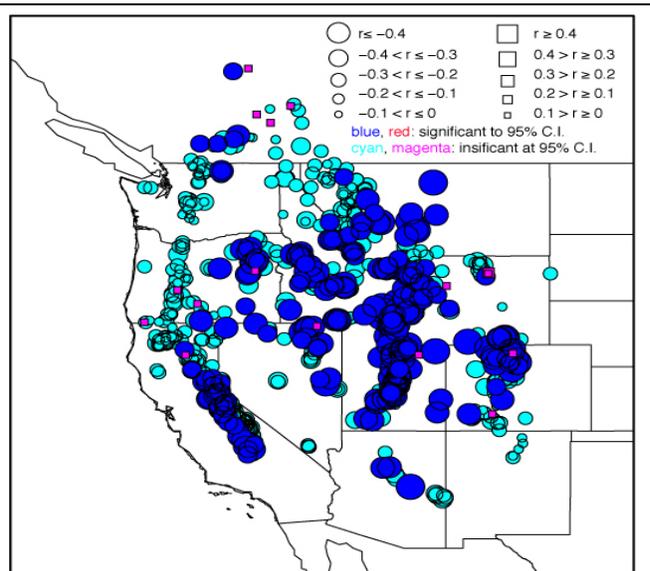
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*It is crucial that we understand the hydrologic response of the Sierra Nevada Mountains—a primary source of fresh water for Southern California—to projected climate change over the next few decades to centuries. This study aims to contribute to this 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 21<sup>st</sup> century leaves this region highly vulnerable to severe drought and the resulting environmental damage and socioeconomic disruption. Much of Southern California's fresh-water 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. This study aims to contribute to the understanding of hydrologic response of the Sierra Nevada to projected climate change over the next few decades 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.

Two primary goals of this project are to: 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.

Having collected 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 compiled at the Limnological Research Center (LRC) at the University of Minnesota, Minneapolis and analyzed to create a time series of varve thick-



Correlation of National Water and Climate Center SNOTEL station April 1 Snow Water Equivalent values from 1949-2006 with Swamp Lake sediment  $\delta D$  over the sample time period.

ness 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 ( $\delta D$ ) from a specific organic compound, probably from terrestrial and aquatic plants around the perimeter of the lake, was measured over the 20<sup>th</sup> century as sampled from the upper core sediments in order to compare  $\delta D$  with known variability from the instrumental climate record. Comparison of the preliminary  $\delta D$  series April 1 Snow Water Equivalent records reveal significant negative correlations, indicating the years with low snowfall deposit sediments enriched in deuterium, as expected under our hypothesis. These results suggest, therefore that lipid  $\delta D$  from the lake sediments may reflect snowfall amount and periods of aridity sustained over multiple years.  $\delta D$  measurements of plant and lake water sample from the Swamp Lake watershed provide further constraint when assigning climatological mechanisms to observed 20<sup>th</sup> century  $\delta D$  variability. We have begun to measure  $\delta D$  from Medieval aged sediments, deposited between 900 and 1400 AD, from the same suite of cores. We find significant decadal scale  $\delta D$  variability over this time, and using the linkages established through the 20<sup>th</sup> century measurements, we can reconstruct precipitation and aridity patterns over these centuries. Overall, 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, Christopher Charles and R. Scott Anderson, Modern Swamp Lake Cores: Lake Sediment D/H Ratios, A potential Tracer for Decadal Scale Hydroclimate Variability in the Sierra Nevada. American Geophysical Union PACLIM conference, Pacific Grove, CA, April 2009.

Roach, Lydia, Daniel Cayan, Christopher Charles and R. Scott Anderson, Modern Swamp Lake Cores: D/H Ratios from Sierra Nevada Varved Lake Sediments Record Decadal Scale Hydroclimate Variability During the Medieval Period. American Geophysical Union conference, San Francisco, CA December 2009.

### **Collaborative Efforts**

Field work in Yosemite National Park (YNP) was permitted by the National Park Service. Logistical support was provided by Jan Van Wagendonk of the USGS and by Jim Roach, Josh Bacchi, and Sam Seimens of YNP. Considerable support, including coring and raft equipment was provided by Scott Anderson of Northern Arizona University. Core Processing facilities and storage was provided at the University of Minnesota LRC Core Facility. Hydrogen isotope analysis is carried out in direct collaboration with Alex Sessions at the California Institute of Technology; all sample processing and  $\delta D$  measurements are made in his lab.

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## Control of Mercury Methylation in Wetlands through Iron Addition

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*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 exist 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 important 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, high levels of MeHg production often occur in wetlands, 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 iron to wetland sediments. After iron addition, the concentration of dissolved sulfide decreases through the formation of  $\text{FeS}_{(s)}$ . 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.

Over the past year, we completed a laboratory microcosm experiment using tidal wetland sediments that started in spring 2008. We found significant reductions in methylmercury concentrations exported in the surface water from the medium and high iron dose groups (amended with 360 and 720 g-Fe/m<sup>2</sup>, respectively) relative to the unamended control. At the end of the experiment, we sampled sediment cores from the microcosms to assess the formation of iron-

sulfur minerals between the different amendment groups. We found evidence of enhanced production of acid-volatile sulfur (ie,  $\text{FeS}_{(s)}$ ) and pyrite (ie,  $\text{FeS}_{2(s)}$ ) in the iron-amended microcosms, which could have further implications for reducing methylmercury output as these minerals can be important sorption sites for inorganic mercury. We also conducted a second microcosm experiment using the same laboratory microcosm system with intact sediment cores containing live wetland plants (pickleweed), which supported the results of the sediment-only experiment.

This project demonstrated that the addition of ferrous iron to tidal wetland sediments has the potential to provide a practical landscape-scale control that could be implemented during tidal wetland construction and restoration projects throughout California. However, further research is needed to determine the efficacy of an iron amendment under in-situ field conditions, as well as in a variety of tidal wetland types, before this technique can be applied successfully.

### **Professional Presentations**

Ulrich, Patrick and David Sedlak, Decrease in net mercury methylation following an iron amendment to wetland microcosms, San Francisco Estuary Institute Regional Monitoring Program Mercury Coordination Meeting, Oakland, CA, February 2009

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

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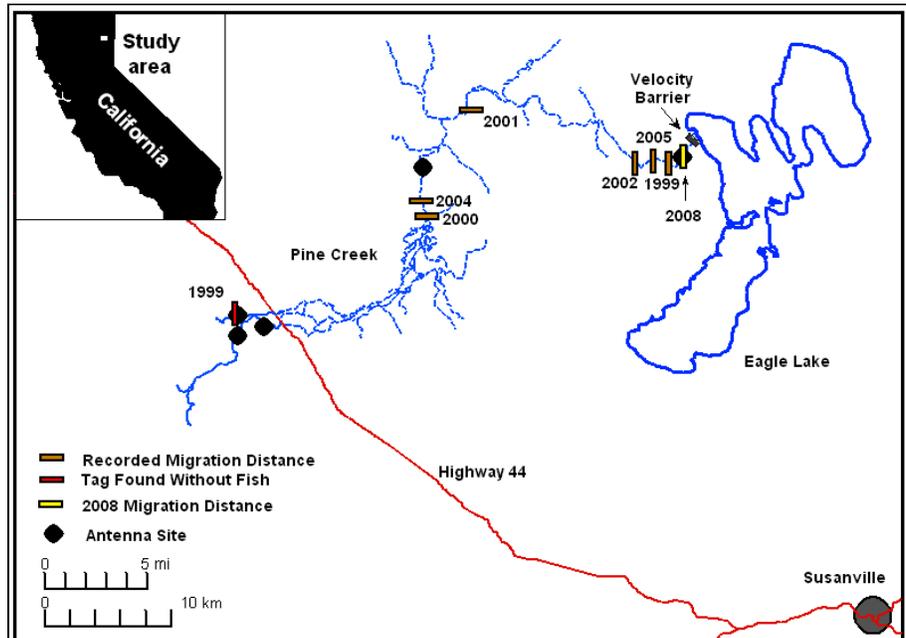
*This is the final year of a study to test whether the numerous watershed restoration activities conducted during a 20-year effort in the Pine Creek watershed (Lassen County) have provided conditions under which Eagle Lake rainbow trout can complete their natural life cycle.*

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. 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.

We worked at a watershed scale to determine the management actions necessary for the restoration of spawning and rearing of ELRT. Our main objectives were 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 surgically implanted with PIT tags and released upstream of the passage barrier. Upstream migration was monitored with five channel-spanning stationary PIT antennas.



Map of Eagle Lake and Pine Creek watershed showing antenna locations and migration distances.



Lisa Thompson tags an Eagle Lake rainbow trout spawner.

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.

We studied the rearing of ELRT juveniles with and without non-native brook trout, in the spawning and rearing habitat of the upper watershed. In August 2007, we electrofished all of Bogard Spring Creek, a small tributary of Pine Creek, to assess fish abundance, and removed all the brook trout that we cap-

tured. 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 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.

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.

### **Professional Presentation**

Thompson, Lisa, Craig Fergus. Restoring a rangeland watershed & its endemic rainbow trout in the face of climate change: Eagle Lake Rainbow Trout and Pine Creek. Salmonid Restoration Federation conference. Santa Cruz, CA. March 6, 2009.

### **Collaborative Efforts**

This project involves and expands on existing relationships with collaborators including the Pine Creek Coordinated Resources Management Planning Group, California Department of Fish and Game, US Forest Service, Natural Resource Conservation Service, Susanville Indian Rancheria, and numerous volunteers. These groups made extensive in-kind contributions of time volunteered on field work. US Forest Service staff 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.





# The Transport and Fate of Current-use, Sediment Bound Pesticides into a Coastal Marine System

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*Current-use pyrethroid pesticides are being transported into the marine environment from agricultural and urban applications in the surrounding watersheds via river suspended solids. Sediment collected only a few miles upstream of the mouth of coastal rivers contained concentrations of these pesticides acutely toxic to some invertebrates. However, no detectable amounts of pyrethroids were found in marine benthic sediments of Monterey Bay, probably due to dilution and further pesticide degradation.*

The purpose of the investigation was to determine whether current-use pesticides, used in both agriculture and urban areas, are being transported by suspended solids into the marine environment. Focusing on pyrethroid insecticides, the study examines their transport by coastal rivers on to the shelf of Monterey Bay, and then finally into the deep marine canyon.

#### *Procedures:*

Pyrethroid pesticides are used in both agriculture and urban settings. These current-use insecticides are known to be transported into creeks and rivers at amounts toxic to invertebrates, especially amphipods. However, in coastal watersheds in which pyrethroids are used, no work has been done to study the further transport downstream into the marine environment. The Monterey Bay has three major watersheds which have distinctly different watershed land-uses. The San Lorenzo River watershed includes mostly open spaces full of coastal redwoods and one major city, Santa Cruz. The Pajaro River watershed is mainly agricultural and residential. The Salinas River supports a large area of agriculture, known as the "salad bowl of America," and a couple major cities, including the city of Salinas.

The first part of the experiment included sampling water from all three rivers during

major rain events in 2008 and 2009. The sample sites were about one to two miles away from the mouths of each major river to represent what would reach the ocean, but were upstream beyond the range of saltwater influence. The suspended solids were centrifuged out of the water and analyzed for pyrethroids. Bed sediments were sampled in Elkhorn Slough (through which the Salinas River usually flows), at many locations throughout shelf depths of Monterey Bay, and in the Monterey Canyon

#### *Freshwater to Marine Transport:*

Analysis of suspended sediment samples indicates that toxic amounts of pyrethroids are being transported in river water to the ocean. Nearly all samples contained pyrethroids, and they were present on suspended sediment at concentrations that would be acutely toxic to sensitive benthic invertebrates if exposed to those sediments after deposition. The pyrethroids bifenthrin and permethrin were most frequently found, though several other pyrethroids were present in occasional samples. There was no unique signature of pyrethroids unique to each river, for all contained similar compounds. Also, it appeared that permethrin and cypermethrin had been used more heavily in the months leading up to the 2007/2008 rainy season, than during the 2008/2009 rainy season.

### *Bed Sediment Analysis:*

Due to the hydrophobicity of pyrethroids, the primary sink for these insecticides would be in bed sediments. Bed sediments in the innermost portions of Elkhorn Slough, at the point where agricultural drainages enter the system contained pyrethroids, most notably bifenthrin, permethrin, and esfenvalerate. Those sample sites that had pyrethroids, were found to be slightly toxic when tested with the marine amphipod, *Leptocheirus plumulosus*, though the concentrations were sufficient to cause high mortality in other species for which pyrethroid sensitivities are reported in the literature.

Marine benthic samples were taken using a modified Van Veen grab sampler, while deep sea marine canyon sediments were taken using a remote operating vehicle and corers. The majority of this sampling was done during the summer and fall of 2007, and the spring of 2008. Historical samples from years of higher rainfall, including samples from 2005 and 2006, were also analyzed for pyrethroids. Toxicity tests with *L. plumulosus* showed no toxicity, and chemical analysis of these sediments found no detectable amounts of pyrethroids in these samples.

### *Significance of Findings:*

Transport of pyrethroid pesticides is well documented into freshwater creeks and rivers close to areas of application. However, this study shows that pyrethroids are being transported further downstream, reaching the periphery of Monterey Bay. However, while pyrethroids are entering the marine system on suspended sediment following rain events, once those sediments are deposited on the shelf and in the canyon, pyrethroids are no longer present at measurable concentrations due to dilution. Pyrethroids are known to move from their point of application to freshwater systems. They could have negative effects on freshwater communities of the rivers, and confined shoreline embayments, like portions of Elkhorn Slough. They are unlikely to have acute effects on open water marine com-

munities of Monterey Bay, and chronic effects, if any, would be difficult to demonstrate since they could occur at concentrations below current detection thresholds.

### **Collaborative Efforts**

We would like to thank Dr. Michael J. Lydy and his lab at Southern Illinois University for their guidance and the use of their laboratory to do the chemical analysis. Thanks to Dane Hardin of the Central Coast Long-term Environmental Assessment Network for helping set up boat time on the R/V Fulmar, and for his help as a field assistant. Thanks to the crews of the R/V Fulmar and the R/V John Martin for their great work which made collection of the marine samples possible. The deep-sea samples would have been impossible without the help and generosity of Dr. Charlie Paull, Dr. James Barry, the whole Benthic Ecology Group at MBARI, the crews of the R/V Western Flyer, R/V Point Lobos, and the pilots of the ROV Ventana, and ROV Tiburon. Finally, we are very grateful for all the field assistants who were able to volunteer their time: Aundrea Asbell, Dennis J. Evangelista, James Kreft, Jenny McGuire, Jennifer Skene, and Lindsay Waldrop.

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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.





# Securing Access to Water Institutional Strategies for Coping with Drought

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*Analysis of legal, institutional and management issues surrounding strategies to augment water supply during a drought, including groundwater recharge and conjunctive management, resulted in a proposal to establish a strategic groundwater reserve to mitigate severe water shortages. A more detailed analysis followed of current approaches to reduce vulnerability to drought by three north and central coast water agencies.*

The first phase of this project examined the institutional framework for drought planning in California and the legal requirements, policy tools and management approaches utilized by the state, local water suppliers and individual water users to achieve a reliable water supply during prolonged water shortages. Analysis demonstrated that throughout the state, current approaches fail to promote the establishment of sufficient buffers to reduce vulnerability to extreme drought events. Groundwater recharge and storage, along with an innovative strategy - the establishment of strategic groundwater reserves - were proposed to increase long-term water supply security during extended dry periods. This would include 1) bringing groundwater basins into hydrologic balance through recharge processes, 2) developing metrics and incentives to establish and maintain a groundwater reserve. State authority to establish the reserve was delineated, including Article X, Section 2 of the California Constitution, and other sections of the California Water Code.

The second phase of the project focused on current approaches to reduce vulnerability to drought by three water agencies, the Sonoma County Water Agency (SCWA), the City of Santa Cruz Water Department and the Pajaro Valley Water Management Agency (PVWMA). The two coastal regions served by these agencies share a climate

characterized by great physical and biological heterogeneity, with almost no rain in the summer and periodic long-term physical droughts. The central coast agencies do not import water whereas the Sonoma County Water Agency on the north coast receives water from the Eel River via the Potter Valley Hydropower Project. None of the agencies import water from the state or federal water projects, leaving them especially vulnerable to a severe drought.

### *City of Santa Cruz Water Department*

The City of Santa Cruz Water Department receives its water primarily from the San Lorenzo River and north coast streams. It has one reservoir with a modest storage capacity that was built in 1960 when the population was 31,000. Today the department serves ~90,000 residents, and projections anticipate that water demand will increase. It is the only municipality around Monterey Bay that does not rely heavily on groundwater. Its main problem is that surface runoff and storage do not furnish an adequate supply during dry years. The City's Drought Emergency Ordinance reflects a typically reactive approach to planning for water shortages, requiring that rules to conserve water be put into effect when a lack of sufficient rainfall, runoff and reservoir storage result in inadequate supplies to support normal water needs. The city proposes that future needs could potentially be

satisfied by conservation, full development of existing supplies, and new supplies. Yet, after a 3-year drought, its available supply, which is limited by reservoir storage, would extend to only one additional dry year. As a result, the city is exploring a conjunctive management project with the adjacent Soquel Creek Water District that involves the construction of a desalination plant. In contrast to the City of Santa Cruz, Soquel Creek has access to groundwater resources, but lacks a large surface water supply. Conjunctive management would provide desalinated water to Soquel Creek during wet years when Santa Cruz receives its water from normal precipitation. Soquel Creek would use wet year water in lieu of pumping groundwater, thereby recharging its aquifer. During dry years, Santa Cruz would use the desalinated water and Soquel Creek would use its groundwater to supply its constituents.

#### *Pajaro Valley Water Management Agency (PVWMA)*

The Pajaro Valley relies on ground water for nearly all of its water supply. Agriculture uses about 85% of the resource (about 50,000 acre feet per year) and residential and commercial users consume the rest. Ground water levels in the Pajaro Valley are below sea level much of the year, and in some areas of the coast seawater intrusion extends as much as 2 miles inland. In 1980, the State Department of Water Resources identified the Pajaro Valley Basin as one of eleven basins with critical conditions of overdraft. The increase in population in the four major cities of the watershed – Watsonville, Hollister, Gilroy, and Morgan Hill, along with the development of rural and agricultural areas reliant on ground water, contributed to the overdraft, as did a shift in the types of crop grown. Because no single agency had jurisdictional authority to manage the entire ground water basin, in 1984, voters approved the formation of PVWMA to manage existing and supplemental water supplies in order to prevent an increase in, and to reduce long-term overdraft, land subsidence, and water quality degradation,

and to ensure sufficient water supplies. A recycled water program was established after decades of planning and significant state and federal grant funding. In September 2009, the Watsonville Area Water Recycling Facility began delivering tertiary treated, disinfected recycled water through the Coastal Distribution System for use in irrigation. However, when the PVWMA raised rates to fund its programs, it was sued by local citizens and it lost in litigation. As a result, it is working on finding a more acceptable funding mechanism to enable it to reduce the still significant ground water overdraft in the valley.

#### *Sonoma County Water Agency (SCWA)*

The SCWA is the main entity responsible for supplying Russian River water to about 570,000 people throughout Sonoma County and neighboring Marin County. The region has experienced rapid population growth, accelerated urbanization and agricultural development over the past few decades. Until very recently the agency relied on imported Eel River water stored in Lake Mendocino reservoir to recharge its underlying aquifer. It also relied on water stored in a second reservoir, Lake Sonoma. The listing of both Eel and Russian River salmonids under the Endangered Species Act resulted in mandates by the National Marine Fisheries Service to (1) reduce Eel River flows into the Russian River, (2) reduce summertime flows in the mainstem Russian River and on Dry Creek (the conduit for Lake Sonoma water), and (3) enhance habitat on Dry Creek. This led to an increased effort by the agency to diversify its water supply and management strategies, including both conservation and the conjunctive management of surface and ground water. Ground water conditions have changed significantly since the state conducted studies 20–25 years ago, and there is current concern regarding the degradation of water quality from seawater intrusion, high nitrate concentrations, and mixing with waters high in mineral content. The agency is working with scientists from the U.S. Geological Survey to evaluate ground water resources in several basins to

develop a detailed understanding of the ground-water/surface-water system, including the Santa Rosa Plain, and Sonoma Valley.

### *Analysis*

Each agency's approach to water supply planning has been influenced by its legacies of access along with its region's physical, economic and demographic characteristics. Increasingly, state and federal mandates and funding have provided strong incentives for each agency to move in specific directions. Thus Federal Endangered Species Act requirements were one important catalyst for the SCWA to propose a modification of its pending State Water Resources Control Board application for additional water rights, and to put on hold its plans for a new transmission system to move water from Lake Sonoma to the Russian River. Instead it is pursuing a diverse set of strategies, including ground water studies, as a way to secure a more sustainable and long-term supply for the region. Likewise, the state's Urban Water Management Plan requirements were a factor in the City of Santa Cruz' decision to explore a more proactive drought planning strategy through a conjunctive management partnership with neighboring Soquel Creek. With the help of government funding, PVWMA is now also able to implement its plan to utilize tertiary treated water for irrigation. However, after losing litigation regarding its rates under Proposition 218, the agency needs to find an acceptable funding mechanism to solve the ground water overdraft in the Pajaro Valley, balance the basin, and stop seawater intrusion. While all the agencies are attempting to move towards more sustainable water supply management, at this time none of the agencies have specific plans to establish reserves to reduce their vulnerability to an extended drought.

### **Publications**

Ruth Langridge, "Confronting Drought: Water Supply Planning and the Establishment of a Strategic Groundwater Reserve," *University of Denver Water Law Review*, Volume 12 Issue 2, Spring 2009

### **Collaborative Efforts**

A collaborative effort has been initiated with Professor Andrew Fisher in the Department of Earth and Planetary Sciences at the University of California, Santa Cruz for the next phase of this research. We have also had discussions with Professor John Dracup, Department of Civil and Environmental Engineering at the University of California, Berkeley, and Dr. Larry Dale at Lawrence Berkeley Laboratories for new work on the energy costs of pumping groundwater.

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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; the Bay Area IRWMP 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.*

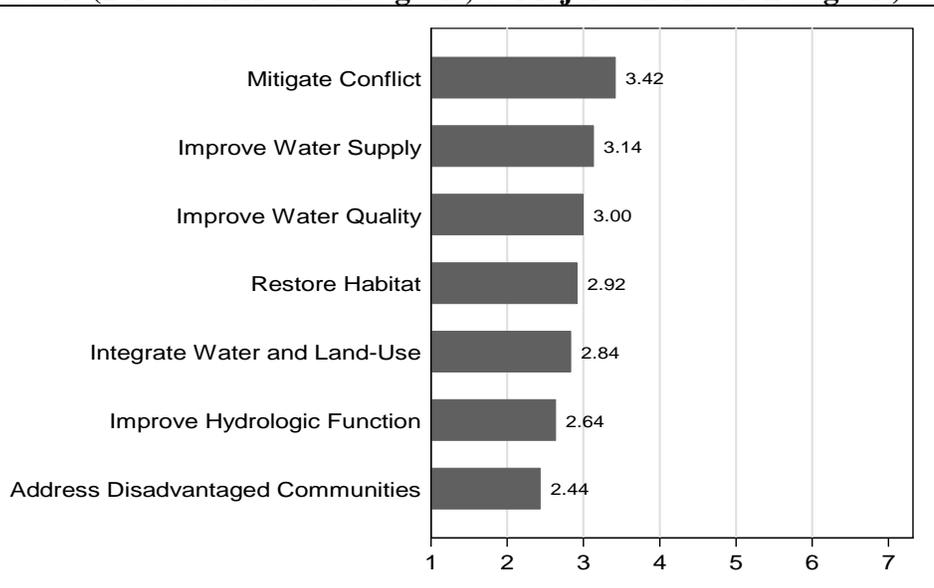
The goal of this project is to use theories of institutions and collective action to understand the factors contributing to the effectiveness of Integrated Regional Water Management Planning (IRWMP) in California. IRWMP provides state grant funding to local stakeholders to develop integrated regional 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 questions: 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.

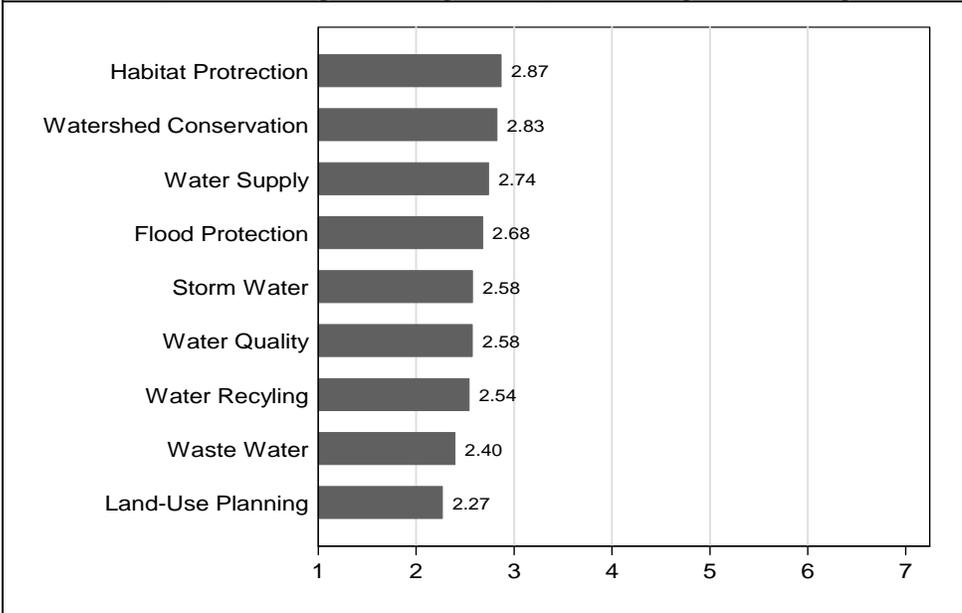
On the other hand, stakeholders indicate that the IRWMP has increased levels of trust and policy networks, which may be critical to future water management decisions. It may be too early to expect widespread increases in integration and collaboration;

**Figure 1: Perceived IRWMP Contribution to Water Management Goals (1=No contribution to goals; 7=Major contribution to goals)**



building an initial basis may be enough for now. Furthermore, the distribution of priority projects that emerged from the IRWMP 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.

**Figure 2: Perceived IRWMP Success at Integration of Watershed Functions (1=No change in integration; 7=Much greater integration)**



<b>Table 1: Reasons for IRWM Failures and Successes</b>	
<i>Negative Views on IRWM</i>	
State guidelines for IRWM were clear and understandable.	2.77
State guidelines for IRWM were sufficiently flexible to accommodate regional differences	2.77
IRWM was too time consuming	4.79
My participation in IRWM had a large influence on decisions.	2.25
IRWMP was controlled by narrow interests.	4.42
<i>Positive Views on IRWM</i>	
IRWM has helped me network with other stakeholders.	4.4
IRWM has improved the level of collaboration among Bay Area stakeholders.	4.6
Note: Responses provided on a Likert scale where 1= strongly disagree and 7=strongly agree.	

**Publications**

Lucas, Lippert. "An Assessment of Integrated Regional Water Management Planning (IRWMP) in the San Francisco Bay Area." UC Davis Master's Thesis, 2008.

**Professional Presentations**

Lubell, Mark, and Lucas Lippert. "Integrated Regional Water Management: Collaboration or Politics as Usual?" Annual Meeting of the American Political Science Association, Toronto, Canada, 2009.

Lubell, Mark. "Water Management in an Ecology of Games." Harvard Networks in Political Science Conference, Cambridge, MA, 2009

**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.

**For further information please contact:**

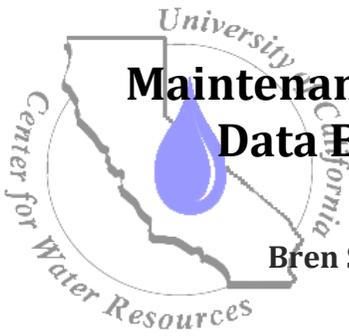
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# Special Projects

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

Gary D. Libecap  
Bren School of Environmental Science and Management  
University of California, Santa Barbara

*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 graduate student Zachary Donohew to compile and maintain a 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 – December 2008. There are 4,175 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 (2,728 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](http://www.bren.ucsb.edu/news/water_transfers.htm) and the WRRC website at [http://www.lib.berkeley.edu/WRCA/WRC/research\\_sp.html](http://www.lib.berkeley.edu/WRCA/WRC/research_sp.html).

The dataset and website are continually updated.

## **Publications**

Grafton, Quentin, Clay Landry, Gary D. Libecap, and R.J. O' Brien, "Water Markets: Australia's Murray Darling Basin and the U.S. Southwest," submitted to *Journal of Economic Perspectives*, 2009.

Donohew, Zachary, "Property Rights and Western U.S. Water Markets," *Australian Journal of Agricultural and Resource Economics*, 2009, 53: 85-103.

Brewer, Jedidiah, and Gary D. Libecap, "Property Rights and the Public Trust Doctrine in Environmental Protection and Natural Resource Conservation," *Australian Journal of Agricultural and Resource Economics*, 2009, 53: 1-17.

Libecap, Gary D. "The Tragedy of the Commons: Property Rights and Markets as Solutions to Resource and Environmental Problems," *Australian Journal of Agricultural and Resource Economics*, 2009, 53: 129-44.

## **Professional Presentations**

Libecap, Gary D. "Water Transactions," Hong Kong Polytechnic University, December 2008.

Libecap, Gary D. "Water Transactions," Oregon State University, January 2009.

Libecap, Gary D. "Water Transactions," Australia Consumer and Competition Commission, August 2009.

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# Salinity/Drainage Program

This program encompasses research and/or extension activities that address and contribute to the resolution of the salinity-drainage-toxics problem in the western San Joaquin Valley and elsewhere in California. Topics include policy analysis and systems optimization of sustainable salinity and drainage management options for the western San Joaquin Valley; fate and impacts of various trace element chemical species in the environment; long-term management of retired lands; relative impacts of boron on the long-term consequences of using drainage water for irrigation; and technology development for real-time monitoring of water for chemical constituents of concern.





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

Christopher Amrhein and Yiqiang Zhang  
Department of Environmental Sciences  
University of California, Riverside

*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.*

Effective and economical removal of selenium (Se) in agricultural drainage water is very important in Se bioremediation. Zero valent iron (ZVI) and a redox mediator [anthraquinone-2,6-disulfonate (AQDS)] were assessed for their ability to enhance the removal of Se(VI) or Se(IV) (500  $\mu\text{g/L}$ ) in synthetic drainage water by *Enterobacter taylorae*. The results showed that *E. taylorae* was capable of using inexpensive sucrose to remove Se from the drainage water. During a 7-day experiment, Se(VI) was almost entirely reduced to Se(0) and transformed to organic Se in the drainage water with a sucrose level of 500 to 1000 mg/L. Addition of ZVI to the drainage water increased the removal of total soluble Se to 94.5-96.5% and limited the production of organic Se. Addition of AQDS to the drainage water with or without ZVI decreased Se(VI) removal, but enhanced the removal of Se(IV), suggesting that *E. taylorae* only can use anthra-hydroquinone-2,6-disulfonate (AHQDS, a reduced form of AQDS) to respire Se(IV), and not Se(VI). These results show that ZVI has promising application potential in the bioremediation of Se in Se-contaminated water. Recently, we found that *Bacillus* sp. RS1 was capable of using AHQDS to reduce Se(VI) (data not shown in this report), accelerating Se removal from agricultural drainage water.

## Publications

Zhang, Y.Q. C. Amrhein, A. Chang, and W.T. Frankenberger, Jr. 2008. Effect of zero-valent iron and a redox mediator on

removal of selenium in agricultural drainage water. *Sci. Total Environ.* 407:89-96.

## Professional Presentations

Bioavailability, sorption, and soil redox chemistry of tungsten and tungsten metal-alloys in two California soils. M.H. Davis, A. Dellantonio, C. Amrhein, and D.R. Parker. Soil Science Society of America Annual Meeting, Houston, TX. Oct. 6-10, 2008.

Biogeochemistry of tungsten alloys in soils. A. Dellantonio, M. Davis, and C. Amrhein. Goldschmidt Conference, Davos, Switzerland. June 21-26, 2009.

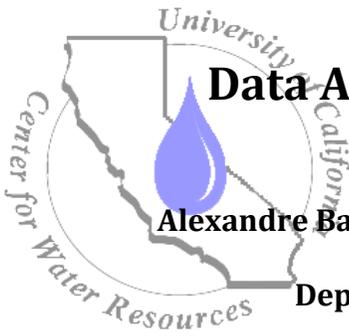
## Collaborative Efforts

This project has helped us get 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). This work has expanded into other redox-sensitive elements found in soils including molybdenum and tungsten, for which we have received additional funding.

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# Data Assimilation for Shallow Water Flows using Lagrangian Sensing

Alexandre Bayen, Andrew Tinka, Qingfang Wu, Olli-Pekka Tossavainen  
 Julie Perceley, Tarek Rabbani, Issam Strub  
 Department of Civil and Environmental Engineering  
 University of California, Berkeley

*The goal of this project is to design, implement and test data assimilation algorithms which can reconstruct two dimensional shallow water flows using Lagrangian (mobile) and Eulerian (static) measurements. Special attention has been paid to the requirements of practical implementation of data assimilation methods. 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 data assimilation to reconstruct currents and other features, such as salinity, in real time.

Our data assimilation algorithms seek to incorporate all the possible measurement information available to a flow model of the river. The result is an estimate of the state of the river.

To increase the performance of the data assimilation algorithm with real data collected from the Sacramento River, so called modeling error needs to be taken into account. Modeling error arises from the use of a lightweight computational model to approximate the true river flow. This approximation, however, is necessary for computational efficiency of the algorithm. The modeling error was characterized using a three-dimensional flow model (MIKE3 from DHI Software) as a ground truth. The results show that modeling error is captured and it

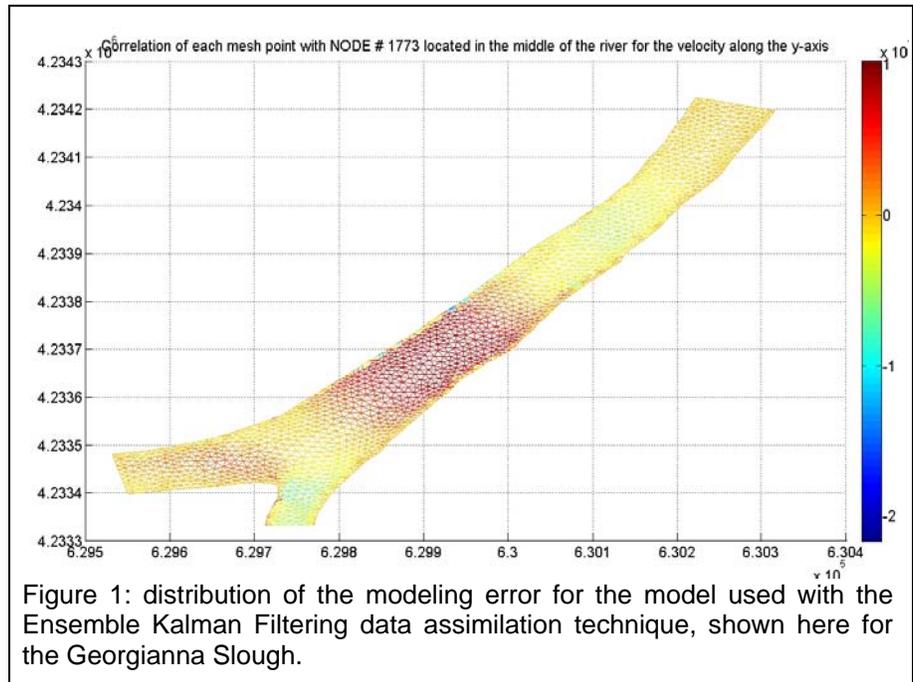


Figure 1: distribution of the modeling error for the model used with the Ensemble Kalman Filtering data assimilation technique, shown here for the Georgianna Slough.

enables the use of real data without any additional tuning of the data assimilation algorithm. The results in Figure 1 show that the characteristics of the error are nontrivial and have to be obtained through extensive modeling. Especially, the correlations between different parts of the river play a significant role. (Velocity units are in m/s.)

Algorithms developed as part of this work are tested in deployments, which for the Sacramento Delta are performed in the Georgianna Slough and the Grant Line Canal. Additional deployments have included the Federal Agriculture Department's Hydrologic Engineering Research Unit, Stillwater, OK, in a joint operation with the US Army Corps of Engineers, and the Department of Homeland Security.

The project has so far developed three generations of drifters, which started with purely passive data logging drifters. This was expanded to communication and control enabled drifters (Figure 2). The third generation drifter also includes motors and a buoyancy control mechanism.

### **Publications**

Issam Strub, J. Percelay, O.-P. Tossavainen, A. Bayen, Comparison of two data assimilation algorithms for shallow water flows, *Networks and Heterogeneous Media*, 2009, (4)2, pp. 409-430.

Issam Strub, J. Percelay, M. Stacey, A. Bayen, Inverse estimation of open boundary conditions in tidal channels, *Ocean Modelling*, 2009, 29(1), pp. 85-93.

Qingfang Wu, X. Litrico, A. Bayen, Data reconciliation of an open channel flow network using modal decomposition, *Advances in Water Resources*, 2009, 32(2), pp. 193-204.

### **Professional Presentations**

Olli-Pekka Tossavainen, 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, *47th IEEE Conference on Decision and Control*, pp. 3903-3910, Cancun, Mexico, Dec. 2008

### **Collaborative Efforts**

The research performed as part of this project is a joint collaboration with Professor Mark Stacey, CEE, UC Berkeley, Dr. Peter Schwartz, Lawrence Berkeley National Laboratories, and Dr. Eli Ateljevich, California Department of Water Resources. Some of the deployments performed as part of this work are jointly done with the US Army Corps of Engineers, and the Department of Homeland Security.



Figure 2: EECS Ph.D. student Andrew Tinka demonstrates the capabilities of the UC Berkeley drifters prior to their deployment, Stillwater, OK.

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# Mechanism of Boron Toxicity in Crop Plants

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*Excess boron (B) in irrigation waters negatively impacts growth of processing tomato; however the impact of the timing of application of B on crop response is poorly understood. Tomato exposed to boron during early and mid-crop development yielded less crop and accumulated less boron than tomato exposed during the later stages of development. In agricultural systems with access to diverse irrigation sources, use of poorest quality irrigation water late in the season is preferable.*

In the western San Joaquin Valley, growers have access to irrigation sources that vary in quality from low salt – low boron (B) surface and irrigation district sources, to high salt – high B ground waters. The goal of the present investigation was to determine the relative impact of high B applied at different stages of tomato growth and development. Results suggest that application of high B water at later stages of plant growth and development will have significantly less impact on plant yield than the application of high concentrations of B at earlier growth stages. Total quantity of applied B irrigation and total accumulation of B in above ground parts was higher when B was applied late in the crop development.

## Procedures

A tomato B toxicity response study was conducted with processing tomatoes in a greenhouse at Davis, CA.

The experiment had five treatments applied to processing tomatoes grown from transplanted seedlings for 105 days to full maturity. Treatments were:

1. Control: continuous 0.5 ppm B.
2. Continuous high B: two weeks of 8 ppm B, then 3 weeks of 12 ppm B, repeated for three cycles.
3. Early stage high B: two weeks of 8 ppm B, then 3 weeks of 12 ppm B for the ini-

tial 5 weeks of growth followed by 0.5 ppm for 10 weeks.

4. Mid stage high B: five weeks of 0.5 ppm B followed by two weeks of 8 ppm B, then 3 weeks of 12 ppm B and five weeks of 0.5 ppm B.
5. Late stage high B: ten weeks of 0.5 ppm B followed by two weeks of 8 ppm B, then 3 weeks of 12 ppm B for the last five weeks of growth.

## Key findings

**Fruit yield:** Late stage high B (treatment 5) had yields equivalent to control B treatments and significantly higher fruit yield than either continuous high B (treatment 2), early (treatment 3) or middle stage high B (treatment 4). Control and continuous high B treatments resulted in yields that were 100 % and 68% greater than high B treatments applied during early and mid growth stages. In addition, there was a greater percentage of large and mature green fruit on the continuous high than on all other B treatments,

**Vegetative growth:** The application of high B at the late stage of crop growth resulted in significantly higher leaf, stem and root dry weight than continuous high B, mid or early stage high B. However, there was no difference between control and the late stage high B application.

Fruit characteristics: Control and late stage high B had significantly higher percentage of big fruits (>50 grams) than either continuous high B, middle or early stage high B.

Tissue B analysis: In all treatments, B was mainly accumulated in the leaf and stem tissues. Under continuous or mid stage B application, fruits accumulated significantly more total B than other treatments. In all treatments, B accumulated predominantly in leaf tissue, representing 88-90% of the whole plant B. Among the three different high B treatments (early, mid, late), the late stage high B treatment accumulated the highest amount of B both in the leaf and whole plant.

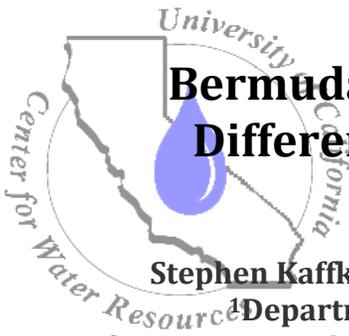
### **Significance**

The growth stage at which high B containing irrigation water is applied, has a significant effect on plant growth, yield and total B contained in above ground tissues. Application of B during early and mid stage crop growth resulted in significantly reduced shoot and fruit growth while late season applications resulted in growth and yields not significantly different from plants grown under low B conditions. Continuous high B application also resulted in significant accumulation in shoot and fruit tissues. High B accumulation in fruits grown with high B treatment will contribute to the removal of B from the field.

Under conditions where two or more sources of irrigation water of differing quality is available, productivity in tomato can be maximized by utilizing the best quality (low B) water for early growth and the poorer quality (high B) water for later growth. Since the demand for water also increases as crops mature, this strategy also allows for consumption of a greater volume poor quality water, thereby reserving higher quality water for use in more sensitive crops or growth stages. Using this strategy, productivity losses can be minimized while the utilization of the poor quality water can be maximized.

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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

Stephen Kaffka<sup>1</sup>, Maximo Alonso<sup>1</sup>, Stephen Grattan<sup>2</sup> and Dennis Corwin<sup>3</sup>

<sup>1</sup>Department of Plant Sciences, University of California, Davis  
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<sup>3</sup>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.*

In 2007 a container trial under different salinity and nitrogen levels was implemented at UC Davis campus to supplement field trials. 48 pots of 56.8 l were filled with soil collected at the field site in Western San Joaquin Valley. The soils corresponded to three salinity levels: 7, 14 and 22 dS m<sup>-1</sup>. The pots were seeded with Bermuda grass on May 2007 and irrigated with 2 l of a synthetic saline water solution of 6 dS m<sup>-1</sup> 2-3 times a week. The fertilization regime was equivalent to 0, 300 and 600 kg N ha<sup>-1</sup>. The pots were harvested every 4-6 weeks at 1 cm to estimate grass growth for the different treatments. The forage samples were divided in leaves and stems and sub-samples were analyzed at the ANR laboratory on the UC Davis campus to determine their nutritional value. We repeated the experiment in 2008 using the same containers with Bermuda grass to study the effect of boron, selenium and molybdenum on the forage yield and quality.

After two consecutive growing seasons in the containers, Bermuda grass under frequent irrigation with synthetic saline water (6 dS m<sup>-1</sup>) and fertilized with the equivalent to 600 kg N ha<sup>-1</sup>

yielded 20 ton DM ha<sup>-1</sup> in a soil of 7 dS m<sup>-1</sup> ECe (Figure 1). With a fertilization equivalent to 300 kg N ha<sup>-1</sup> yields were close to 16 ton DM ha<sup>-1</sup>. Without fertilization yields were around 1 ton DM ha<sup>-1</sup>. An increment in soil salinity from 7 to 22 dS m<sup>-1</sup> ECe reduced yield by 15% and 7% with and without fertilization respectively.

The leaf/stem ratio (LSR) is a traditional index of forage quality. We used the container trial to evaluate the proportion of leaves and stems in 2007 and 2008. Results were similar in both years. LSR was significantly different (p<0.05) between unfertilized and fertilized treatments (Figures 2 and 3). The difference between fertilized treatments (300

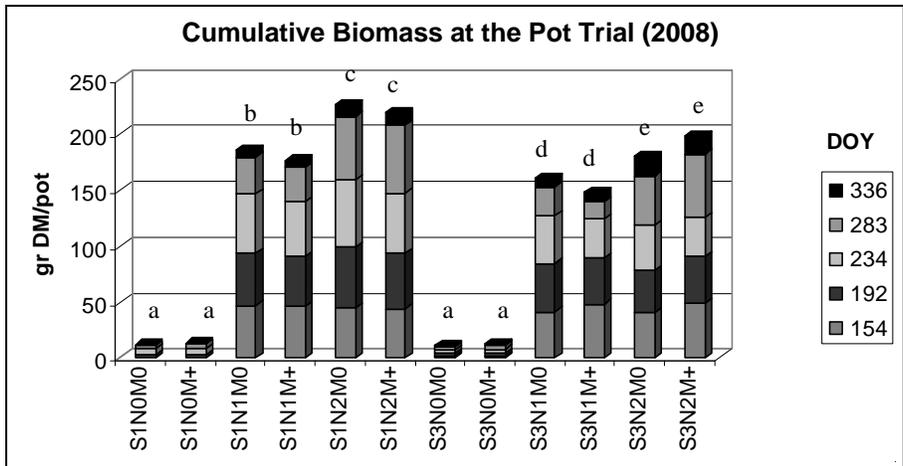


Figure 1. Bermuda grass cumulative biomass in a pot trial under different salinity and nitrogen levels in 2008. S1: 7 dS m<sup>-1</sup> ECe; S3: 22 dS m<sup>-1</sup> ECe; N0: 0 kg N ha<sup>-1</sup>; N1: 300 kg N ha<sup>-1</sup>; N2: 600 kg N ha<sup>-1</sup>; M0: No trace minerals; M+: Trace minerals. DOY: Day of the year. Columns with the same letter are not significantly different (p>0.05).

and 600 kg N ha<sup>-1</sup>) was not significant (p>0.05). The differences in LSR at different soil salinity levels (7, 14 and 22 dS m<sup>-1</sup>) was not significant (p>0.05) also.

Nitrogen fertilization not only increases yield, but changes the aerial composition of Bermuda grass (Figures 4 and 5). Results of the pot trial indicate that nitrogen fertilization

increases the proportion of leaves by 20% and decreases the proportion of inflorescences by the same percentage. The proportion of stems is not affected. Although the differences in the aerial composition between fertilized and unfertilized treatments were significant (p<0.05), they were not significant (p>0.05) between treatments fertilized with 300 and 600 kg N ha<sup>-1</sup>. Differences in aerial composition between soil salinity levels were not significant (p>0.05).

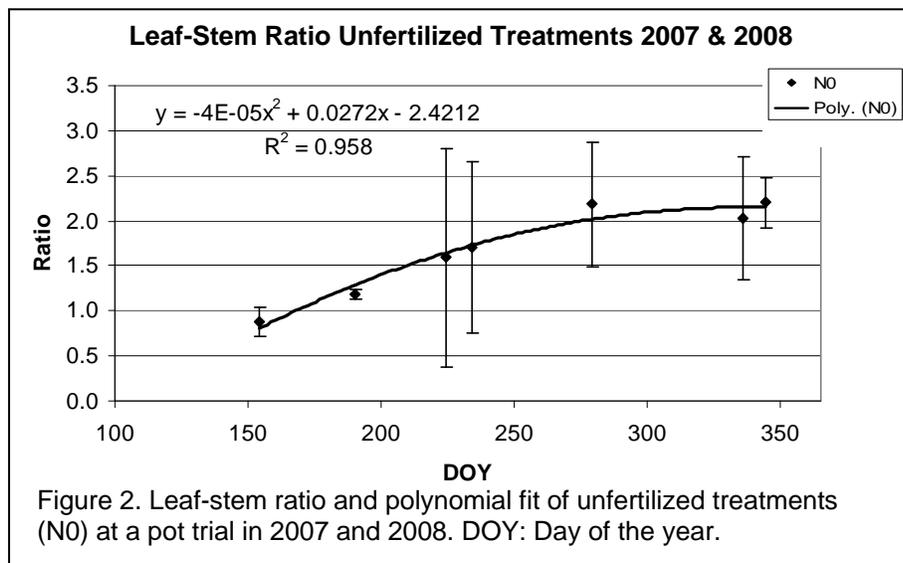


Figure 2. Leaf-stem ratio and polynomial fit of unfertilized treatments (N0) at a pot trial in 2007 and 2008. DOY: Day of the year.

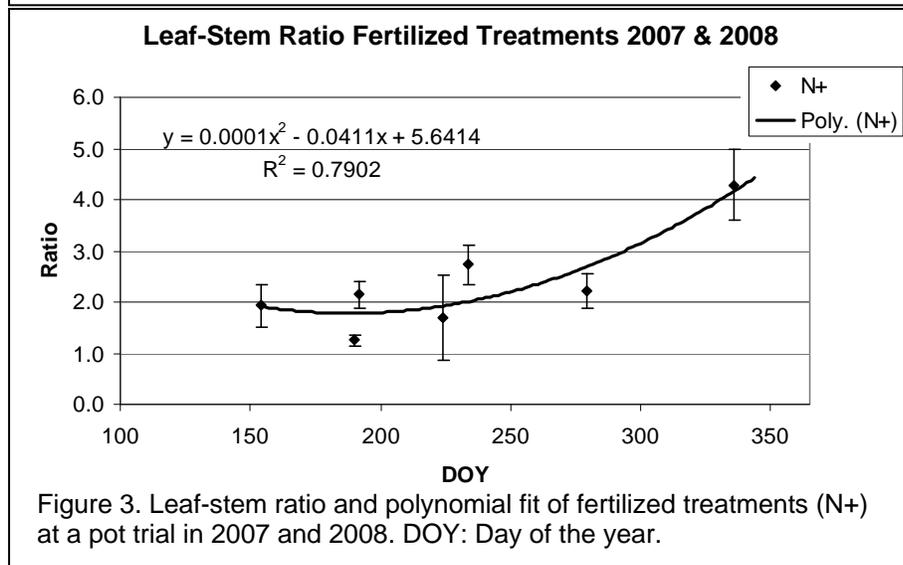


Figure 3. Leaf-stem ratio and polynomial fit of fertilized treatments (N+) at a pot trial in 2007 and 2008. DOY: Day of the year.

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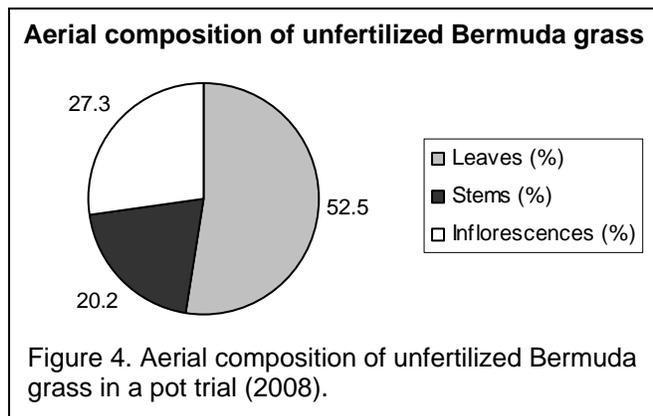


Figure 4. Aerial composition of unfertilized Bermuda grass in a pot trial (2008).

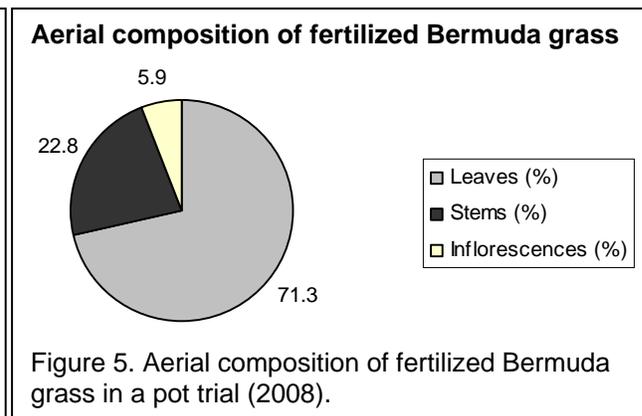


Figure 5. Aerial composition of fertilized Bermuda grass in a pot trial (2008).



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

Hugo A. Loaiciga, P.I. Professor

Thomas Pingel (Ph.D. student); Elizabeth Garcia (Ph.D. student)

Department of Geography

University of California, Santa Barbara

*This study simulated the effect of sea-level rise on the Seaside Area sub-basin near the city of Monterey, California. The simulation was carried out with a state-of-art, finite-element, variable-density, numerical model that accounts for the effects of salinity on groundwater density and viscosity.*

The California Department of Water Resources (2006) predicted a rise in mean sea level along California's coastline ranging from 10 to 90 cm over the 21<sup>st</sup> century due to rising global mean surface temperature. The rise in sea level threatens coastal aquifers by exacerbating the risk of saline intrusion. This study simulated the effect of sea-level rise on two coastal aquifers of California: the Seaside Area sub-basin near the city of Monterey, and the Oxnard Plain sub-basin near the city of Ventura. The simulations were carried out with a state-of-art, finite-element, variable-density, numerical model that accounts for the effects of salinity on groundwater density and viscosity. Seawater intrusion was simulated for various scenarios of sea-level rise, varying from 0 m to 1 m. Each scenario contemplated the same level of predicted groundwater extraction through the 21<sup>st</sup> century in the study aquifers. The numerical simulations of seawater intrusion indicate that one meter of sea-level rise would contribute an additional 10 to 15 meters of inland spread of the 1,000 mg/L saline front and 20 to 30 meters of the 10,000 mg/L saline front. The effect of sea-level rise on seawater intrusion, therefore, appears minor when compared with historical measurements of seawater intrusion caused primarily by groundwater pumping since the early 1900s.

## **Publications**

Loaiciga, H.A., Pingel, T., Garcia, E. Assessment of Seawater Intrusion Potential From Secular Sea-Level Rise in a Coastal Aquifer of California. Water Resources Research, in press.

## **Professional Presentations**

Loaiciga, H.A., Pingel, T., Garcia, E. "Assessment of seawater intrusion potential from sea level rise and pumping in coastal aquifers of California", presented at the "Groundwater salinity: a groundwater dilemma" Conference of the UC Center for Water Resources and Ground Resources Association of California, Sacramento, California, March 24-25, 2009.

Loaiciga, H.A., Pingel, T., Garcia, E. 21<sup>st</sup> century sea level rise, economic growth, and seawater intrusion", Fall Meeting American Geophysical Union, San Francisco, California, Dec. 15, 2008.

Loaiciga, H.A., Pingel, T., Garcia, E. "21<sup>st</sup> century sea-level rise and seawater intrusion in coastal aquifers of California". Symposium on Climate Change Implications for California Groundwater Management, California Groundwater Resources Association of California, Sacramento, California, August 13, 2008.

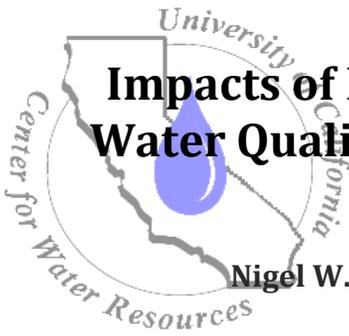
## **Collaborative Efforts**

A research proposal was submitted to NASA NSPIRES in collaboration with the University of Idaho, the University of Alaska, the University of New Hampshire, and UCSB. The research proposal will target the Tarim River basin in China, and its water resources, socio-economics, and climate change processes in that river basin.

A workshop on the Tarim River basin of China was funded by the National Science Foundation, November 22-27, 2009, to bring together US, Chinese, and Central Asian researchers to discuss and share scientific knowledge on the world's largest closed river basin, the Tarim river basin.

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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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California Polytechnic State University, San Luis Obispo

*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 tim-

ing 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<sub>4</sub><sup>+</sup>, NO<sub>2</sub><sup>-</sup>+NO<sub>3</sub><sup>-</sup>, organic), phosphorus (total, PO<sub>4</sub><sup>3-</sup>), total organic carbon, alkalinity, turbidity, temperature, and pH. Planktonic and benthic 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 *Daphnia*. 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, 988lbs, 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, 2009. Environmental decision support system development for seasonal wetland salt management in a river basin subjected to water quality regulation. *Agricultural Water Management*, 96 (2), p.247-254, Feb 2009.

### **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 California Department of Fish and Game, John Eadie from UC Davis, and Laura Castro and Ernie Taylor from the California 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 off this excessive saline recharge to the groundwater leads to a gradual rise in the water table eventually encroaching upon the root zone. This may ultimately make the land unfit for any productive 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 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 manage-

ment for drainage impaired land is proposed. With this “bottom up 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 property change with average soil water salinity.

### **Publications**

Singh, P. N., W. W. Wallender, M. P. Maneta, S. L. Lee and B. A. Olsen. 2009. Sustainable root zone salinity and shallow water table in the context of land retirement, Journal of Irrigation and Drainage Engineering ASCE, In Press.

### **Professional Presentations**

Singh, Purnendu and Wesley Wallender Land retirement in the west San Joaquin Valley: Role of soil hydraulic properties and attenuation for sustainable root zone salinity, American Society of Agricultural & Biological Engineers (ASABE) annual international meeting, June 21-June 24, 2009 Reno, Nevada.

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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.





# Assessing Orchard and Vineyard Irrigation Needs with Thermal Aerial Imagery

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Land, Air and Water Resources  
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*From June 29 to July 3, 2009, we conducted flights over three different permanent crops in the San Joaquin Valley: almonds, grapes, and pistachio. This work was made possible by the visit of a team from CSIC, Cordoba, Spain. The Spanish group provided the drone aircraft, cameras, and associated equipment; we provided the team that took ground-based measurements of plant water status to compare with the remotely sensed stress indicators. The equipment and dedication of the Spanish team allowed us to not only compare remotely sensed stress indicators taken at different elevations but also on different crops and different times of the day.*

On June 25, 2009, the unmanned aerial vehicle (UAV) team from Spain, consisting of Pablo Zarco, team leader, two technicians (back up pilot and computer navigator), and three graduate students, arrived in Fresno. Their first two days were spent visiting the three experimental sites and testing the UAVs and associated systems.

The first experimental flight took place over 640 acres of pistachio at AgriWorld, Inc., in Madera. There were two 320 acre blocks. On one block, the irrigation frequency of the microsprinkler system had been increased by a factor of two, resulting in a range of tree stresses across the 10 irrigation sets. The other 320 acre block was irrigated with the grower's regular frequency and, thus, used to evaluate tree stresses that would normally occur. There were two pairs of flights made; pairs referring to flights of both the UAVs with the thermal infrared and multispectral cameras. Flights were made at 1000 ft altitudes. Ground measurements were made of tree stress with pressure chambers using a team of three people, each with ATV mounted instruments. Initial inspection confirmed that all aerial sensors were working properly.

The second experimental flights were conducted on an existing almond irrigation project at the Belridge Ranch of Paramount Farming Co., Inc. There were four pairs of

flights: 10:00 am, Noon, 2:00 pm, and 4:00 pm. The flights monitored plots exposed to five different irrigation levels. There were eight replications of each irrigation regime with each replication had four monitored trees. A team of 10 technicians, each with an ATV-mounted pressure chamber, took a total of 240 individual tree measurements during each of the four pairs of flights. Initial data analysis showed a good correlation between tree stress measured with the aerial imagery and the ground-based readings.

We returned to the AgriWorld pistachio site the next day and conducted the same measurements as previously. This was done to observe differences in the spatial distribution of tree stress with the aerial imagery; to determine if the time course development of stress resulted in differences in coefficients of variation.

The fourth experimental flights took place at the Kearney Agricultural Center on grapes surrounding the weighing lysimeter. The objective was to not only observe the correlation between aerial and ground based indicators of stress but also to allow for comparison of actual evapotranspiration (ET<sub>c</sub>) made with the lysimeter and calculated ET<sub>c</sub> based on the aerial measurements of canopy temperature (the so called METRIC and SEBAL approaches).

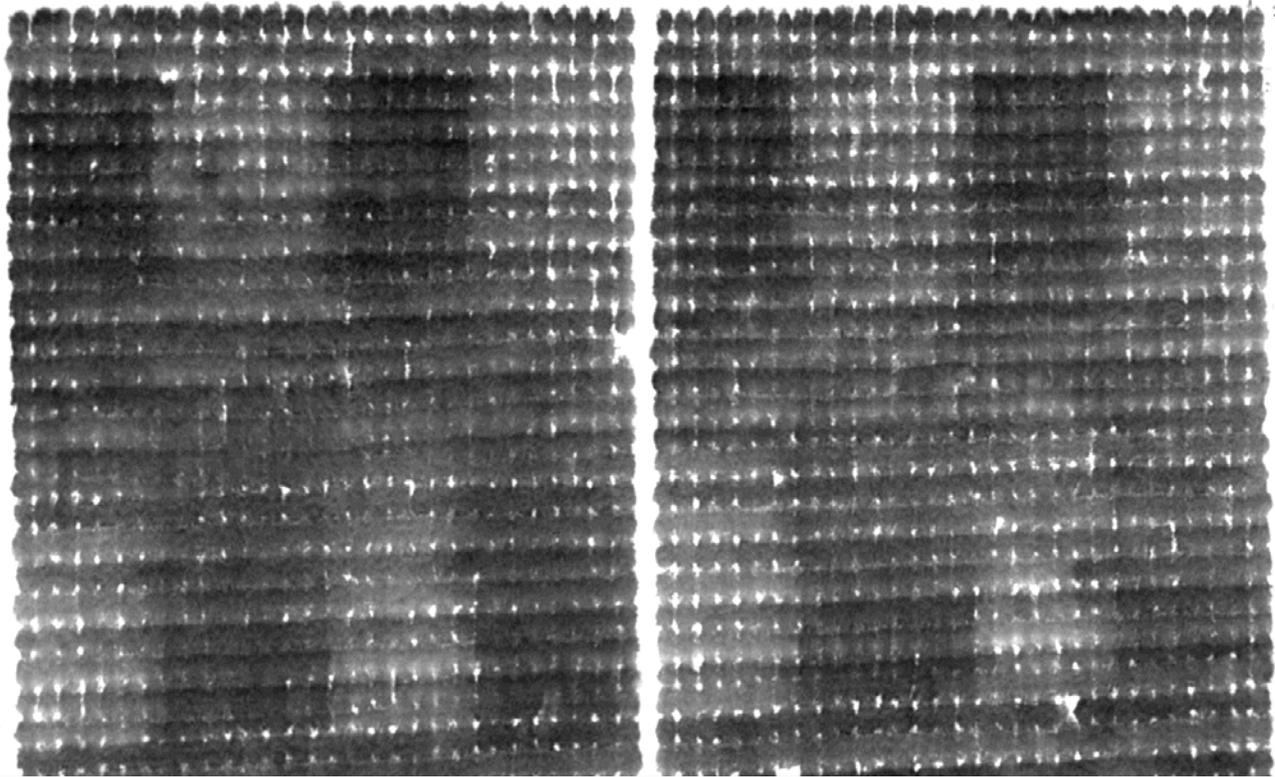


Fig. 1. Thermal aerial image (grayscale) of almond orchard with existing irrigation treatments. There are eight replications of 10 irrigation regimes on each of two cultivars (1:1 row planting configuration). In Rep. 1, treatments move from low to high irrigation from top to bottom. In Rep. 2, treatments move from high to low top to bottom and this sequence repeats itself for remaining replications. Darker pixels are cooler temperatures, lighter are hotter.

The last set of flights again took place at the AgriWorld pistachio site. In addition to conducting the same measurements as the two previous monitoring days, flights were flown at two elevations to observe differences in analysis as a function of different pixel sizes.

### **Collaborative Efforts**

The team from Spain included Pablo Jesús Zarco Tejada, Elías Fereres Castiel, José Antonio Jiménez Berni, María Dolores Suárez Barranco, Alberto Vera Toscano, David Notario Rosingana, María Victoria González Dugo. UC Davis Dave Goldhamer, Mario Salinas, and Rene Resendez, UC Davis. Kevin Brooks, UC Cooperative Extension Madera County. Richard Paisley and Chris Wiley, AgriWorld, Bakersfield.

### **Publications**

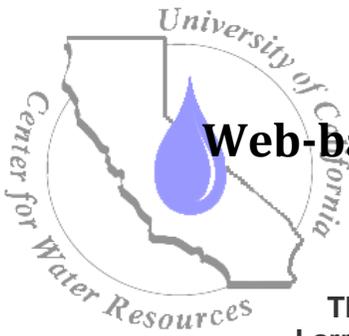
No publications have yet been published, however, a popular press article can be found at:

<http://westernfarmpress.com/environment/water-management-0805/>.

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# UC Irrigation Water Management Web-based Research and Information Center (IrRIC)

Stephen Grattan, Mary Bianchi, Louise Ferguson,  
Thomas Harter, Loren Oki, Terry Prichard, Blake Sanden,  
Larry Schwankl, Pia van Benthem, Manager, and Laosheng Wu

*A web-based Irrigation Research and Information Center is currently being developed at the University of California. The goal is to develop an educational outreach and extension service to facilitate and coordinate the dissemination of research-based information, educational material and activities related to irrigated agriculture.*

The University of California (UC) has been at the forefront in research and extension in areas related to irrigated agriculture over the past century. Valuable information has been developed over the years not only on the Davis and Riverside campuses, but within various counties and Research and Extension Centers across the state. This information, however, is scattered among manuals, reports, leaflets, manuscripts and books and much of this information is not readily available to the agricultural community. There are some individuals who have recently developed websites that address their particular area of expertise and some of that website contains valuable irrigation-related information. However there is no central location where users can readily find useful research-based information on all aspects of irrigation water management.

Our objective is to develop a user-friendly web-based Research and Information Center (RIC) that will provide users with practical irrigation water management information. Much of the research-based information would be that developed by UC ANR (Davis and Riverside

campuses, and Counties) but the site will include links to other useful resources. The goal is to develop an easy to navigate website that links the user to useful information while at the same time, showcases the University with its historical and continued leadership in irrigation management, both in terms of leading research and extension activities.



The intended users of the website will be the general public, as well as irrigation advisors, consultants, educators, State, Federal and Local agencies and professionals related to various aspects of irrigation water management and surface and ground water quality as it relates to agriculture.

The department of Land, Air and Water Resources at UC Davis will house the web-based center and the major construction of the web-based center will be developed over a two-year period.

The "Steering Committee", names listed as Co-PIs on project above, will serve as key resources in their general area of expertise and will provide the Project Manager with key irrigation-related material to be posted or linked to on the website. The Steering

Committee has approved a mission statement (see below), a web-site logo (see image) and a general outline of the material/links to be posted. Key individuals have been contacted and the hired web-designer and manager have already begun contacting and collecting important information to post on the site.

**Mission Statement:** The University of California Irrigation Research and Information Center is an educational outreach and extension service to facilitate and coordinate the dissemination of research-based information, educational material, and activities related to irrigated agriculture.

### **Professional Presentations**

van Benthem, P. et al. 2009 IrRIC poster presentation. California Climate Change Research Symposium 9 September 2009 Sacramento, CA.

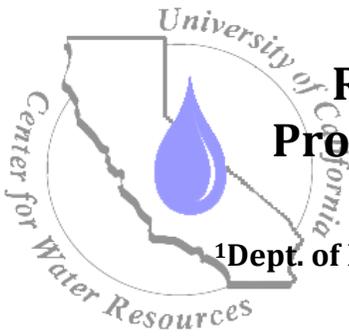
### **Collaborative Efforts**

A collaborative effort with Dr. Troy Peters, Extension Irrigation Specialist, WSU and Irrigation Specialists at Oregon and Idaho to develop a Regional Pacific Northwest Irrigation web-based Center has been initiated.

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

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*Yields of 'Washington' navel orange trees receiving 25% and 40% less irrigation water than the well-watered control trees by either partial root zone drying (PRD), or conventional irrigation at reduced rates (CI-RR) were significantly reduced. The lower irrigation rates, independent of PRD or CI-RR, also reduced the yield of commercially valuable large size fruit. The negative effects of reduced irrigation on yield resulted when treatments were imposed July to January or January through December. This year to prevent the reduction in fruit size, the amount of irrigation water given to trees in the PRD and CI-RR treatments was increased to that of the well-watered control trees during August and September. With this strategy, fruit growth rate recovered for trees that previously received 50% PRD from January through July, resulting in fruit with an average diameter equal to that of the well-watered control trees by September, while using 27% less irrigation water than the well-watered control trees from January through September.*

The California citrus industry produces "picture perfect" navel orange fruit for the fresh fruit market on 124,385 irrigated acres. The cost of irrigation water is a major expense associated with citrus production. Partial root zone drying (PRD) is an irrigation strategy designed to increase water-use efficiency in fruit tree crops to reduce production costs without reducing the current or return yield. PRD is the practice of alternately wetting and drying the root zone on two sides of the tree.

Our research goal is to test the feasibility of using partial root zone drying (PRD) to reduce the amount of water used in citrus production and, thus, increase grower net income. The specific objectives are: (1) to reduce annual water use in a commercial navel orange orchard by alternately wetting and drying the root zone on two sides of the tree using irrigation rates that are 25% or 40% less than the well-watered control under conventional irrigation (CI); (2) to compare the PRD treatments with CI at the reduced rates (CI-RR) of 25% and 40% less than the well-watered control and with the well-watered control; (3) to determine the effect of PRD and CI-RR treatments on soil

moisture content to schedule irrigation; (4) to 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) to provide the initial soil moisture content values and number of calendar days for scheduling irrigation for PRD or CI-RR; and (6) to provide a cost:benefit analysis of the results.

The design is a randomized complete block with five replications of each treatment 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 that alternate in delivery to one side of the tree and then the other; (4) 75% CI-RR and (5) 60% CI-RR – trees have an emitter on each side of the five trees within the row 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 five replications. For years 1 (July-January) and 2 (January-December), controls were irrigated when soil moisture reached -30 cb at 30 cm; PRD

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

Treatment	Packing carton size <sup>y</sup>					
	Total	56	72	88	113	138
	----- no. of fruit/tree -----					
Control	1142.97 a <sup>z</sup>	27.91 a	100.97 a	263.08 a	374.33 a	375.59 a
CI-RR 75%	809.38 b	7.88 b	28.85 b	95.84 b	225.81 b	450.78 a
CI-RR 60%	107.93 c	0.36 b	2.76 b	14.40 c	27.79 c	62.62 b
PRD 75%	127.15 c	0.12 b	2.14 b	9.09 c	36.22 c	79.57 b
PRD 60%	130.03 c	0.52 b	2.04 b	14.80 c	33.83 c	78.84 b
<i>P</i> -value	<0.0001	0.0003	<0.0001	<0.0001	<0.0001	<0.0001

<sup>y</sup> Fruit sizes categories based on transverse diameters (cm): 138 (<6.35), 113 (6.35-6.89), 88 (6.9-7.49), 72 (7.5-8.09), and 56 (8.1-8.8).

<sup>z</sup> Values in a vertical column followed by different letters are significantly different at the specified *P*-value by Fisher's Protected LSD Test.

Table 2. Effect of reduced irrigation (75% and 60% of the well-watered control) by CI or PRD on total gallons of water applied and fruit size.

Treatment	1 Jan- 31 Mar	1 Apr- 30 Jun	1 Jul- 30 Sep	12 Jun	13 Jul	28 Sep
		----- cumulative gallons applied -----			----- fruit diameter (mm) -----	
Control	26680	54365	71320	31.71 a <sup>z</sup>	42.75 a	57.17 a
CI-RR 75%	10180	41074	59686	28.49 ab	37.41 b	52.25 b
CI-RR 50%	9520	28502	51438	24.37 c	31.24 c	47.38 c
PRD 75%	14810	40800	59726	25.69 bc	33.77 c	48.88 c
PRD 50%	8370	27726	52095	29.81 a	38.81 b	57.07 a
<i>P</i> -value	NA	NA	NA	0.0077	<0.0001	<0.0001

<sup>z</sup> Values in a vertical column followed by different letters are significantly different at specified *P*-value by Fisher's Protected LSD Test.

and CI-RR treatments were allowed to dry to -60 cb before irrigation.

Washington' navel orange trees receiving 25% and 40% less irrigation water than the well-watered control trees from January to December by either PRD, or CI-RR had significantly lower total yield and yields of commercially valuable large size fruit (Table 1). The data indicate that the reduced irrigation treatments, independent of PRD or CI-RR, negatively impact fruit number (fruit set) and fruit size (fruit growth).

For the current year, trees in all treatments were irrigated when soil moisture reached -30 cb at 30 cm to reduce the severity of the water deficit experienced by trees in the PRD and CI-RR treatments, but to save additional water the 60% PRD and 60% CI-RR treatments were reduced to 50%.

From 1 January 2009 to 1 August 2009, PRD and CI-RR treatments delivering 25% and 50% less water per irrigation than the well-watered control reduced the total amount of irrigation water applied to 'Washington' navel orange trees by 25%

and 49%, and 25% and 48%, respectively (Table 2). For these treatments, there was a progressive decline in fruit size (transverse diameter), which was manifest in the trees receiving 50% CI-RR and 75% PRD by mid-June, but delayed for trees in the 75% CI-RR and 50% PRD treatments (Table 2). By mid-July, fruit size was significantly reduced for trees in all PRD and CI-RR treatments. Restoring the irrigation to PRD and CI-RR trees to the amount of the control trees for the months of August and September increased fruit growth. The size of fruit on trees in the 50% PRD treatment was not significantly different from the well-watered control trees by the end of September, despite the trees receiving 27% less water than the control trees through the end of September (Table 2). Although fruit produced by trees in all other reduced irrigation treatments remained significantly smaller than the control, the difference in size as a percent of the control was less in September than in July, providing further evidence that this strategy was beneficial. We plan to measure fruit diameter in October and, depending on the results, resume the reduced irrigation rates on 1 November to save additional water during the cooler months with no negative effect on fruit size at harvest in January 2010.

## **Publications**

Research studying treatment effects on the yield of tree crops is not published without a minimum of three years of yield data.

## **Professional Presentations**

This project and the results thus far were presented to stimulate a student discussion on plant responses to water-deficit stress in BPSC 143, upper-division undergraduate plant physiology.

## **Collaborative Efforts**

The contributions of the UC Riverside Agricultural Operations staff and Mr. Eric Jorgenson to the success of our Prosser Trust project continue to be very important.

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

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

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

Observational data on the scale required for agricultural irrigation management is only available via remote sensing platforms. Remote sensing data does not measure crop or water states but rather reflectance or brightness temperature at the surface.

Using a radiative transfer model coupled to the crop model allows for assimilation of the remote sensing observations to update model state estimates.

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

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 been performed. Analyses of different modeling options were explored in four different irrigation implementations. Five seasons of data (2002-2006) were simulated. The four different experiments were analyzed to con-

firm that the output of the model provided realistic predictions of model states.

During this 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.

Most recently we have begun using a new version of DSSAT coupled to a land surface model (provided Prof. Jasmeet Judge at the University of Florida). This new model allows for a more physical representation of the sub-daily processes. The model and assimilation framework will be tested and applied using data obtained during the NASA SMEX02 field experiment.

## **Collaborative Efforts**

Collaboration has begun with Prof. Jasmeet Judge of the University of Florida who has provided us with a new version of the DSSAT model coupled to a land surface model. This model will be used in future applications of the work.

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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?

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*The ability to precisely apply small amounts of water at any time during the crop season is thus a distinct advantage of the overhead system.*

In this Water Resources Center project, we compared an overhead, low-pressure irrigation system with surface furrow irrigation under both no-tillage and conventional tillage for two cycles of a wheat silage / grain corn rotation at the University of California's West Side Research and Extension Center (WSREC) in Five Points, CA. We also characterized the performance of overhead center pivot irrigation systems for tomatoes, corn and cotton in neighboring farm fields at Red Rock Ranch and at Farming 'D'. Overhead irrigation, though currently not common in this region of California, has become the dominant type of irrigation used in many other areas of the world during the past several decades. Christiansen Uniformity (CU) Coefficients, which are commonly used to measure the overall uniformity of water application in overhead systems, for the linear move system in the WSREC study site (Figure 1) ranged from 85 – 93% depending on the nozzle package used and the height at which the nozzles were set above the ground (Figure 2). Similar, though slightly lower CU's were determined in a variety of farm field determinations at Red Rock Ranch.

Smaller amounts of water were applied more frequently using the overhead system than the furrow system in the wheat /corn rotation study. These applications closely matched cumulative ETC and resulted in about 30% less water applied in the overhead system compared to the furrow sys-

tem for both wheat and corn. The bulk of water savings of the overhead system relative to the furrow system occurred during the early season crop establishment irrigations. The ability to precisely apply small amounts of water at any time during the crop season is thus a distinct advantage of the overhead system. Crop growth, as measured by almost daily destructive biomass harvests and periodic leaf area index and canopy cover determinations, was similar in all irrigation and tillage system combinations.

We determined the relative amounts of soil evaporation following wetting to field



Figure 1: Catch-can uniformity determinations under overhead linear move irrigation system at UC WSREC, Five Points, CA

capacity under bare soil and a wheat residue mulch. After a two-week drying period, twice as much water remained in the surface 20 cm of soil under the wheat residue than in the top 20 cm of the bare soil as measured by D and gravimetric water content determinations. Finally, we determined changes in soil water storage during intercrop tillage events between wheat and corn in standard tillage and in no-till systems and found significantly more water in the surface 20 cm under no-till than in the standard tillage systems.

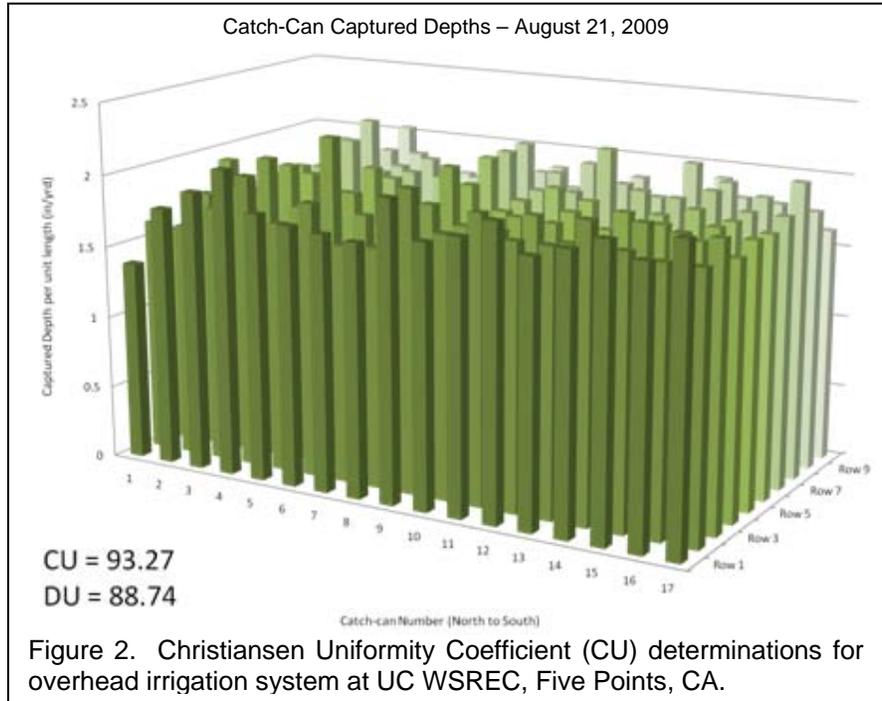


Figure 2. Christiansen Uniformity Coefficient (CU) determinations for overhead irrigation system at UC WSREC, Five Points, CA.

### Professional Presentations

Jeff Mitchell. 2009. Soil management and carbon sequestration. California Ag Climate Symposium. California Climate Symposium. Californai Climate Network. October 1, 2009. Davis, CA.

Jeff Mitchell. 2009. Perspectivas en el desarrollo de la labranza de conservacion. 1er Simposium internacional de agricultura ecologica. September 29, 2009. Ciudad de Obregon, Sonora, Mexico.

Brooks Landers, 2009. Overhead Irrigation. 2009 Agronomic Crops Field Day. University of California West Side Research and Extension Center. Five Points.

Jeff Mitchell. 2009. Coupling overhead irrigation with no-tillage production systems. Water, Money, and Energy Conference. August 12, 2009. Modesto, CA.

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### Collaborative Efforts

The core work of this project has been conducted by a quite diverse group of collaborators including Randy Southard, Karen Klonsky, Wes Wallender, Will Horwath and Jeff Mitchell of UC Davis, Dan Munk, Tom Turini and Kurt Hembree of UCCE Fresno, Five Points, CA farmers, John Diener and Scott Schmidt, and private sector partners, Monte Bottens of CalAgSolutions and Ray Batten, Pat Murray and John Bliss of Valley Irrigation.

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# Development and Application of the Coupled Vadose Zone-Ground Water Flow Modeling Environment: HYDRUS Package for MODFLOW

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*Water flow through the variably-saturated (vadose) zone is an important part of the hydrologic cycle. However, regional-scale groundwater models often simplify or ignore vadose zone flow processes. To overcome this problem, we are developing a new one-dimensional unsaturated flow package for the three-dimensional ground water model MODFLOW, one of the most widely used groundwater flow models.*

Water flow through the variably-saturated zone is an important part of the hydrologic cycle because it influences partitioning of water among various flow components. Depending upon hydrological, geological and soil characteristics, rain and snowmelt is partitioned at the land surface into runoff, infiltration, evapotranspiration, groundwater recharge, and vadose zone storage. Water flow in the vadose zone especially affects the transfer rates between the land surface and the groundwater table, which are two key hydrological boundaries. Evaluation of almost any hydrological process therefore requires that water flow through the vadose zone is appropriately taken into account. However, modeling of vadose zone flow processes is a complex and computationally demanding task that is often handicapped by the lack of data necessary to characterize the hydraulic properties of the subsurface environment. Consequently, vadose zone flow processes have rarely been properly represented in hydrological models. For example, regional-scale groundwater models often simplify vadose zone flow processes by calculating groundwater recharge externally without proper consideration of changes in groundwater levels. To overcome this frequent simplification, there is an urgent need for methods that can effectively simulate water flow through the vadose zone in large scale hydrological

models. This issue is especially important for groundwater models.

To overcome this problem, we are developing a one-dimensional unsaturated flow package for the three-dimensional modular finite-difference ground water model MODFLOW-2000. MODFLOW was developed by the U.S. Geological Survey and is one of the most widely used groundwater flow models. The HYDRUS Package uses the computer program HYDRUS to simulate water movement in variably-saturated porous media by numerically solving the Richards equation. The HYDRUS package considers the effects of infiltration, soil moisture storage, evaporation, plant water uptake, precipitation, runoff, and water accumulation at the ground surface. Being fully incorporated into the MODFLOW program, the HYDRUS package provides MODFLOW with recharge fluxes at the water table, while MODFLOW provides HYDRUS with the position of the groundwater table that is used as the bottom boundary condition in the package. The HYDRUS package provides an optimal trade-off between computational effort and accuracy of model simulations for coupled vadose zone – groundwater problems. Being based on two widely used models for simulating vadose zone flow (HYDRUS) and ground water flow (MODFLOW), the coupled software package has a tremendous potential to become

widely used in both research and management, and to redefine entirely how the complex subsurface flow problems are evaluated.

### **Expected Results:**

There is a wide range of potential applications to which the coupled model (the HYDRUS package for MODFLOW) can be applied. These may include, for example:

- Assessing the threat to water resources from pollution
- Assessing the implications of various climate change forecasts on local water supply
- Evaluating various pollution control measures
- Evaluating the disposal of treated water and its impact on ground water resources
- Evaluating the potential for water storage augmentation by landscape modification
- Evaluating the potential for various augmentations of the water supply
- Evaluating the water needs of ecosystems proposed for protection
- Analyzing existing water supply and demand information to construct a water balance for the catchment or region
- Evaluating the potential for various reductions in water use by conservation
- Evaluating the potential for water reuse

It is indeed impossible to predict at present all potential applications to which the coupled model can be used and all benefits that can follow from its use. When we first released HYDRUS models about a decade ago, we could hardly imagine the wide spread of these models and the diversity of applications. It can be expected, partly because both original models are widely used and represent a state-of-the-art in their respective fields, that the coupled model will be similarly quickly adopted by the public if the four tasks listed above are carried out.

### **Publications**

Twarakavi, N. K. C., J. Šimůnek, and H. S. Seo, Evaluating interactions between groundwater and vadose zone using HYDRUS-based flow package for MODFLOW, *Vadose Zone Journal*, 2008, 7(2):757-768,.

Twarakavi, N. K. C., J. Šimůnek, and H. S. Seo, Reply to Comment on "Evaluating interactions between groundwater and vadose zone using HYDRUS-based flow package for MODFLOW", *Vadose Zone Journal*, 2009, 8(3):820-821.

### **Professional Presentations**

Twarakavi, N. K. C., and J. Šimůnek, A coupled modeling approach for incorporating variably saturated water flow and solute transport in ground water models, XVII. International Conference "Computational Methods in Water Resources, San Francisco, CA, July 6-10, 2008.

Twarakavi, N. K. C. and J. Šimůnek, A coupled approach to modeling vadose zone and ground water flow and solute transport at different scales, Soil Science Society America annual meeting, Houston, TX, October 6-9, 2008.

### **Collaborative Efforts**

We are closely collaborating on this project with Hye Seo, a PhD student at the Colorado School of Mines, Golden, Colorado, and Navin Kumar Twarakavi, Assistant Professor at the Department of Agronomy and Soils, Auburn University, Auburn, Alabama, and Miroslav Sejna at PC Progress, Inc., Prague, Czech Republic.

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