Center for Water Resources
Annual Technical Report
FY 2010

Introduction

The people and resources of the University of California Division of Agriculture and Natural Resources (UC ANR) system serve every county in California. These professionals connect and deliver resources from the entire University of California, forming integrated teams to work on complex issues and develop innovative multidisciplinary solutions. ANR professionals have a unique, proven, respected ability to bring together the resources needed to solve tough problems. They connect with the faculty from the California State University system; private colleges and universities; the staff and resources of federal, state and local government agencies; agricultural, natural resource, and nongovernmental organizations; and others, including leaders and citizens representing environmental, agricultural, youth, and nutrition interests and issues.

ANR Initiative to improve Water Quality, Quantity, and Security California must address our challenges to ensure a high quality of life, a healthy environment, and economic success for future generations. The following multidiscipline, integrated initiative represent the best opportunities for ANR's considerable infrastructure and talent to seek new resources and new ways of partnering within and outside UC to find solutions for California. Water is the life blood of California's economy. As such, water supply and quality for agricultural, urban, and environmental systems is a critical issue facing the state over the next 20 years and beyond. Several issues are paramount:

The supply of water will be limited for all users. Competition for water will intensify among agricultural, urban, and environmental users, with water being transferred from agriculture to the latter two groups. Short-and long-term climate trends will exacerbate the problems associated with water availability Degradation of water quality will become more important as a major public issue. Legal and regulatory decisions will have significant impacts on water use and quality among all sectors.

ANR's role in improving watershed and water management practices and policies includes: Develop innovative scientific techniques, products, and processes to improve water use efficiency and water conservation management practices. Develop and encourage the adoption of management practices that prevent degradation of watersheds and water resources caused by pesticides, salinity, chemicals, animal wastes, nutrients, sediment, and pathogens. Assisting in the development of flexible and effective water policies and strategies using UC'S economic, hydrological, and policy expertise. Science-based research and educational approaches to address these issues in partnership with others, including agricultural groups, environmental groups, and regulatory entities.

Water Resources for California through the NIWR Program for 2010 has focused on areas as outlined below: UC ANR is committed to investing and supporting research and extension work in the areas of water use and water quality as demonstrated in the following:

Individual innovative research projects through UC ANR's academics provide solutions to address water-related issues in California and around the world. ANR's diverse clientele includes farm, nursery, ranch and rangeland, operators and managers; allied industry professionals, public agency representatives, and members of the public. Since the inception of the Water Resources Research Act (WRRA), California has been a significant contributor to one of the most cost-effective, cost-shared national research programs in the country; thus helping multiply the impact of the federal investment.

In 2010, 50 UC Cooperative Extension (UCCE) advisors comprised UC ANR's effort in executing projects related to water; 90 projects focused on water quality and 27 projects targeted water supply and allocation.

ANR s Agricultural Experiment Station (AES) faculty conducted 24 water quality and 11 water use projects.

UC consortium supports nine additional water-related research centers and two water-related programs with the support of approximately 271 faculty members.

Joseph G. Prosser Trust

The Irrigation Management Program, funded by the Joseph G. Prosser Trust, supports a broad spectrum of research related to crop irrigation management, focusing on optimizing yields, conserving water and improving irrigation efficiency. Emphasis is placed on research outputs that improve current practices, and on dissemination of information. Some recent projects funded by this program include:

Coupling automated overhead, low-pressure irrigation systems with conservation tillage; A new irrigation, crop and drainage management paradigm for the Central San Joaquin Valley? (Jeff Mitchell, UC Davis) Toward improved Irrigation Efficiency through Real-time Assimilation of Multi-spectral Satellite Remote Sensing Data into Crop Models (Steven A. Margulis, UCLA) Reducing Water Use in Navel Orange Production with Partial Root Zone Drying Comparison with Conventional Irrigation at the Same Reduced Irrigation Rates (Carol J. Lovatt, UC Riverside and Ben Faber, UCCE Ventura County)

Rosenberg International Forum on Water Policy

The overarching theme of the Rosenberg Forum is to reduce conflict in the management of water resources. Specific sub-themes are chosen by the Advisory Committee for each individual Forum. The primary objective is to facilitate the exchange of information and experience in the management of water resources. The problems of managing and husbanding water are surprisingly common around the world. However approaches and solutions may differ depending upon the available financial resources as well as social and cultural norms. Discussions of alternative approaches and identification of what works and what does not work are intended to aid in devising more effective and efficient water management schemes.

There are two sub-objectives which provide specificity and support in achieving the main objective and in addressing the overarching theme. The first of these is to emphasize the role of science in the making of water policy and in the management of water resources. The second and related sub-objective is to promote exchange and interaction between scientists and policy-makers for the purpose of facilitating the use of science as a basis for the making of water policy. Participants at each Forum are a mix of scientists and policy makers and the presentations and discussions focus equally on illumination of the pertinent science for policy making and on the experience with different policies in different settings around the world.

Research Program Introduction

Collaboration throughout California with the University of California, Agriculture and Natural Resources:

1280 farm, ranch, and rangeland owner/operators and managers, allied industry professionals, public agency representatives, and members of the public, participating in water quality education programs, gained knowledge of best management practices for preserving water quality.

76 farm owner/operators, allied industry and natural resource professionals, and members of the public, participating in water conservation education programs, gained knowledge of water use and conservation practices.

52 farm, nursery, ranch and rangeland owner/operators and managers, allied industry professionals, public agency representatives, and members of the public, participating in water quality education programs, intended to use best management practices for preserving water quality.

California cattle ranchers adopted new grazing practices that improve water use efficiency.

Issue: Most ranchers in the intermountain area of Northern California rely on irrigated pastures or public land grazing allotments for grazing during the growing season. Because of harsh winter conditions, there is insufficient good-quality forage on the range or in irrigated pastures from October to mid April or later. That makes winter feeding one of the most costly inputs in cow/calf cattle operations as ranchers feed hay, low-quality crop aftermath, or supplements. There are other incentives for cattle producers to find alternative grazing systems. Growers are facing continued and more aggressive reductions in public lands grazing. This will intensify the need for improved efficiency and increased forage supplies, especially in the fall. Water use for forage production is also falling under increased scrutiny. A forage system that decreases winter hay feeding, reduces the dependency on public lands grazing, and improves water use efficiency would be highly desirable.

What has been done? UC Cooperative Extension advisors conducted a series of field trials in Siskiyou County to develop a grazing system using winter annual grasses. Trials were conducted with growers and at the UC Intermountain Research and Extension Center. Yield and forage quality were evaluated for several different grass species under actual grazing conditions. Grazing management practices were also studied by cutting to simulate grazing. The results indicated that annual grasses such as triticale could lengthen the forage production season by allowing late fall grazing, early spring grazing and still allow for a hay crop to be produced from the regrowth after grazing. Much of the growing season for winter annual grasses occurs at times of the year when temperatures are cool and rain frequent. Since the amount of water needed per unit of forage is less with this annual grass system than it is with perennial grasses, this system has improved water use efficiency.

Results: The new forage management system, primarily with a new crop called triticale, is a terrific improvement. Triticale doesn t replace an old crop; it complements the traditional cattle grazing systems. Triticale provides grazable forage of high quality when previously that wasn t available. Growth occurs during the year when natural rainfall is more plentiful making better use of water. Its advantages are so great many cattle ranchers are readily adopting the new practices.

University of California research on urban runoff develops improved landscape management practices related to water.

Issue: Recent droughts and expanding urban populations place increasing pressure on California's water supplies. In residential areas, outdoor water use, primarily for landscapes, comprises 50 percent or more of total water use. It is commonplace to see excess water gushing down storm drains from poorly aimed sprinklers, broken sprinkler heads, and a larger volume of water applied than the soil can absorb. The runoff water can carry pesticides, fertilizers and other waste into waterways, causing a detrimental effect on the health of the aquatic life in rivers, lakes and bays.

What has been done? UC researchers, in cooperation with CALFED and the State Water Resources Control Board, examined the runoff from eight neighborhoods in Sacramento and Orange counties. Water runoff samples were collected regularly during the irrigation season and during the first rains of each storm season. The samples were analyzed for 11 pesticides, fertilizers, other pollutants and pathogens. In both counties, UC master gardeners developed activities for homeowners to improve landscape management practices related to water, fertilizer, and pesticide use. The aim was to reduce or eliminate pollution runoff.

Results: The research found runoff flow in both counties showed consistent water waste from normal landscape irrigation. In Northern California, irrigation runoff was nearly five times higher than storm runoff, indicating poor outdoor water management in the dry season. In general, pesticides and pathogen indicators were found in all samples. This data helped water agencies develop customer programs on managing landscapes. Master Gardener outreach improved the landscape practices of homeowners. The flow data also is being used by a team of UC researchers to develop a model for urban planners and developers to reduce water runoff and runoff pollutants in new and existing urban landscapes.

Improving aquifer storage recovery operation to reduce nutrient load and benefit water supply

Basic Information

Title:	Improving aquifer storage recovery operation to reduce nutrient load and benefit water supply
Project Number:	2007CA195G
Start Date:	7/1/2008
End Date:	6/30/2012
Funding Source:	104G
Congressional District:	17th
Research Category:	Ground-water Flow and Transport
Focus Category:	Water Supply, Water Quality, Nitrate Contamination
Descriptors:	
Principal Investigators:	Andrew Fisher, Marc Los Huertos, Charles Geoffrey Wheat

Publications

1. Papers Presented at Professional Meetings (*student co-authors) *Schmidt, C., A. T. Fisher, M. Los Huertos, B. Lockwood, 2008. Processes, controls, and potential for in-situ nutrient removal during managed aquifer recharge to a shallow aquifer, Am. Geophys. Union, Fall Meet. Suppl., Abstracts on CD-ROM.
2. *Racz, A., A. T. Fisher, B. Lockwood, M. Los Huertos, C. Schmidt*, J. Lear, 2008. Quantifying the distribution and dynamics of managed aquifer recharge using mass-balance and time-series thermal methods, Am. Geophys. Union, Fall Meet. Suppl., Abstracts on CD-ROM.
3. Papers Presented at Professional Meetings (*student co-authors) *Schmidt, C., A. T. Fisher, M. Los Huertos, B. Lockwood, 2008. Processes, controls, and potential for in-situ nutrient removal during managed aquifer recharge to a shallow aquifer, Am. Geophys. Union, Fall Meet. Suppl., Abstracts on CD-ROM.
4. *Racz, A., A. T. Fisher, B. Lockwood, M. Los Huertos, C. Schmidt*, J. Lear, 2008. Quantifying the distribution and dynamics of managed aquifer recharge using mass-balance and time-series thermal methods, Am. Geophys. Union, Fall Meet. Suppl., Abstracts on CD-ROM.
5. *Schmidt, C., A. T. Fisher, M. Los Huertos, B. Lockwood, The magnitude and controls on denitrification during managed aquifer recharge into a shallow, unconfined aquifer in a coastal groundwater basin, Am. Geophys. Union, Fall Meet. Suppl., Abstracts on CD-ROM, 14-18 December 2009.
6. *Racz, A., A. T. Fisher, B. Lockwood, M. Los Huertos, C. Schmidt*, J. Lear, Spatial and temporal variations in seepage during managed aquifer recharge, Am. Geophys. Union, Fall Meet. Suppl., Abstracts on CD-ROM, 14-18 December 2009.
7. *Schmidt, C., A. T. Fisher, A. Racz, C. G. Wheat, J. Sharkey, B. Lockwood, Processes and controls on rapid nutrient removal during managed aquifer recharge, 27th Biennial Groundwater Conference, Abstracts with programs, Sacramento, CA, October 6-7 2009.
8. Papers Presented at Professional Meetings (*student co-authors) *Schmidt, C., A. T. Fisher, M. Los Huertos, B. Lockwood, 2008. Processes, controls, and potential for in-situ nutrient removal during managed aquifer recharge to a shallow aquifer, Am. Geophys. Union, Fall Meet. Suppl., Abstracts on

CD-ROM.
9. *Racz, A., A. T. Fisher, B. Lockwood, M. Los Huertos, C. Schmidt*, J. Lear, 2008. Quantifying the distribution and dynamics of managed aquifer recharge using mass-balance and time-series thermal methods, Am. Geophys. Union, Fall Meet. Suppl., Abstracts on CD-ROM.
10. *Schmidt, C., A. T. Fisher, M. Los Huertos, B. Lockwood, The magnitude and controls on denitrification during managed aquifer recharge into a shallow, unconfined aquifer in a coastal groundwater basin, Am. Geophys. Union, Fall Meet. Suppl., Abstracts on CD-ROM, 14-18 December 2009.
11. *Racz, A., A. T. Fisher, B. Lockwood, M. Los Huertos, C. Schmidt*, J. Lear, Spatial and temporal variations in seepage during managed aquifer recharge, Am. Geophys. Union, Fall Meet. Suppl., Abstracts on CD-ROM, 14-18 December 2009.
12. *Schmidt, C., A. T. Fisher, A. Racz, C. G. Wheat, J. Sharkey, B. Lockwood, Processes and controls on rapid nutrient removal during managed aquifer recharge, 27th Biennial Groundwater Conference, Abstracts with programs, Sacramento, CA, October 6-7 2009.
13. *Racz, A. J., A. T. Fisher, C. I. Schmidt*, B. Lockwood, and M. Los Huertos, 2011, The spatial and temporal dynamics of infiltration during managed aquifer recharge, as quantified using mass balance and thermal methods, Ground Water, accepted for publication (pending minor revision).
14. *Schmidt, C. I., A. T. Fisher, A. J. Racz*, M. Los Huertos, and B. Lockwood, 2011, Rapid nutrient load reduction during infiltration as part of managed aquifer recharge in an agricultural groundwater basin, Hydrol. Proc., accepted for publication (pending minor revision).
15. *Schmidt, C., A. T. Fisher, M. Los Huertos, B. Lockwood, Managed aquifer recharge as tool for sustainable management of ground water quantity and quality in agricultural basins, in Towards Sustainable Groundwater in Agriculture, Groundwater Resources Association of California, June 15-17, 2010 San Francisco, CA, p. 154.
16. Langridge, R. and Fisher, A. T., Climate Change, Agriculture and Sustainable Groundwater Management: Groundwater Reserves as a Hedge Against Climate Change and Drought, Eos Trans Am. Geophys. Union, Fall Meet. Suppl., San Francisco CA, H51G-03 (invited), Abstracts on CD-ROM.
17. *Schmidt, C. M.., *Russo, T. A., Fisher, A. T., *Racz, R. J., Wheat, C. G., Los Huertos, M., Lockwood, B. S., Mitigating agricultural impacts on groundwater using distributed managed aquifer recharge ponds, Eos Trans Am. Geophys. Union, Fall Meet. Suppl., San Francisco CA, H53A-0984, Abstracts on CD-ROM.

Research Program

The focus of this research is in improvements that can be made to aquifer storage recovery activities so as to improve both the quantity and quality of water made available to stakeholders. We are collaborating on this research with a local water agency, and with researchers at other academic institutions and the U.S. Geological Survey. The review period included in this summary of results includes the second half of the 2010 water year and the first half of the 2011 water year. Prior to the start of each water year, we have instrumented the base of a managed aquifer recharge (MAR) pond that is used to recharge fresh water into a shallow, perched aquifer. This water is used by local growers in lieu of pumping groundwater from a regional aquifer that is impacted by overdraft and resulting seawater intrusion. The water put into the pond is diverted from a nearby wetland system during the wet (rainy) season, when flows are sufficient high and water quality is good.

We are monitoring the rates of shallow infiltration through the base of the full pond using mass balance techniques, and determining rates of recharge at points along the base of the pond using heat as a tracer. This last technique involves innovative use of time-series analysis to resolve changes in diurnal temperature changes in shallow soils below the pond. We monitor groundwater levels and quality using eight shallow and one deeper monitoring well, arranged spatially around the recharge pond. We have deployed water content, pressure, and thermal sensors around the based of the pond (at nine locations in 2008-09; 22 locations in 2009-10; and eight locations in 2010-11), allowing us to assess rates of infiltration at different locations. We sampled shallow soils before each recharge season and are sampling these materials again at the end of each recharge season to evaluate the influence of recharge on soil grain size, soil carbon content, and hydraulic properties.

In past year we have monitored water quality at multiple locations in the wetland (water source) throughout the water year, in the recharge pond, and in the shallow subsurface using piezometers when the pond is operating. Samples were analyzed for major elements and nutrients, and for nutrient isotopic composition in order to quantify rates of denitrification that occur during recharge. This year we deferred analysis of water quality parameters, and are focusing on improving use of the thermal technique used to assess point-specific infiltration rates into the base of the recharge pond, and quantifying changes in soil hydraulic conductivity during MAR.

Full pond inflitration rates are typically 1–5 m/day during the initial 2–3 weeks after the MAR pond is filled, but decrease rapidly to 0.2–0.4 m/day and remain at this rate for the next 6–8 weeks. In addition, we see large spatial and temporal variations in infiltration rates that sweep across the MAR pond during a 6–8 week period. The greatest rates of infiltration are initially at the northwestern end, but the center of the highest rate of infiltration sweeps across the pond to the southeast, as the magnitude of infiltration rates decreases with time. Grain size analyses of samples collected before and after each recharge season suggest that initial periods of infiltration cause the loss of fine grained material from the upper 50 cm of the subsurface, at the same time as a thin crust of fine sediment accumulates at the base of the pond. The net result is that the overall rate of infiltration slows, and the extent of saturation decreases in the shallow subsurface because the rate of inflow can not keep up with the rate of drainage from below.

Evaluation of fluid chemistry shows that there is a 30-60% load reduction during the passage of water from the pond through the upper 1 m of subsurface soils, and low nitrate water arrives at the monitoring wells surrounding the recharge pond at different times as a function of distance and direction. Nitrate isotopic analyses show that the primary mechanism of nitrate removal is denitrification. Comparison of denitrification rates apparent from our data, based on combined chemical and thermal results, are at the high end of denitrification rates detected in soil and groundwater systems in other settings. It may be that this system is especially efficient at denitrification because of the high availability of organic carbon in the diverted fluids, and the availability of particulate carbon in subsurface soils. We have also found that high rates of denitrification are maintained even at some of the greatest infiltration rates, but that eventually (at the highest infiltration rates), we see the expected decrease in denitrification efficiency.

We have presented results of this work at numerous public meetings and, as a result, there is growing interest regionally in applying what we have learned to other settings.

Invited presentations were made during the reporting period to the following groups, including scientific and engineering personnel and the public at large:

• University of California, Center for Information Technology Research in the Interest of Society (CITRIS), Program Review presentation, Berkeley CA
• Pajaro Valley Water Management Agency, Board of Directors, Watsonville CA
• Two meetings of the Pajaro Valley Water Dialog
• American Geophysical Union Fall Meeting

We were interviewed by the following media groups, generating stories that were published in major newspapers and/or broadcast on the radio:

• Register-Pajaronian (newspaper), Watsonville, CA
• Salinas Californian (newspaper), Salinas, CA

We are in discussion with the Santa Cruz County Resource Conservation District and several stakeholder groups on setting up spin-off projects in other parts of the basin, and are completing a regional GIS analysis and preparing for percolation testing in support of this effort. Development of a new basin management plan is to begin this year, and our studies of MAR will be incorporated into that effort. Finally, we have discussed with staff of the Regional Water Quality Control Board the importance of drafting new agricultural water quality requirements so that they do not prohibit the use of MAR approaches to improve water quality, and this idea has been positively received. We have secured an additional $2000 in funding from the University of California Committee on Research in support of MAR research, and are exploring options for securing funding in support of a broader (distributed MAR) research effort.

Publications and Citations:

We have two papers that have been accepted for publication in peer-reviewed journals, pending submission of minor revisions. Both of these should have revisions submitted by end of May 2011 and will be in press thereafter. We have also made presentations at numerous technical meetings, as listed below. We acknowledge NIWR and support when making all presentations.

A Bayesian approach to snow water equivalent reconstruction

Basic Information

Title:	A Bayesian approach to snow water equivalent reconstruction
Project Number:	2007CA215G
Start Date:	6/1/2008
End Date:	5/31/2010
Funding Source:	104G
Congressional District:	
Research Category:	Climate and Hydrologic Processes
Focus Category:	Hydrology, Surface Water, Water Supply
Descriptors:	
Principal Investigators:	Noah Paul Molotch, Steven Margulis

Publications

1. Molotch, N.P., P.D. Brooks, S.P. Burns, M. Litvak, J.R. McConnell, R.K. Monson, and *K. Musselman, Ecohydrological controls on snowmelt partitioning in mixed-conifer sub-alpine forests, Ecohydrology, in press
2. Veatch, W, P.D. Brooks, *J. Gustafson, N. P. Molotch, Quantifying the effects of forest canopy cover on net snow accumulation at a continental, mid-latitude site, Valles Caldera National Preserve, NM, USA, Ecohydrology, Vol. 2, doi: 10.1002/eco.45, 2009.
3. Molotch, N.P., Reconstructing snow water equivalent in the Rio Grande headwaters using remotely sensed snow cover data and a spatially distributed snowmelt model, Hydrological Processes, Vol. 23, doi: 10.1002/hyp.7206, 2009.
4. Molotch, N.P., T. Meixner, and M.W. Williams, Estimating stream chemistry during the snowmelt pulse using a spatially distributed, coupled snowmelt and hydrochemical modeling approach, Water Resources Research, Vol. 44, doi:10.1029/2007WR006587, 2008.
5. Durand, M., N.P. Molotch, and S. Margulis, A bayesian approach to snow water equivalent reconstruction, Journal of Geophysical Research, 113, doi:10.1029/2008JD009894, 2008.
6. Molotch, N.P., P.D. Brooks, S.P. Burns, M. Litvak, J.R. McConnell, R.K. Monson, and *K. Musselman, Ecohydrological controls on snowmelt partitioning in mixed-conifer sub-alpine forests, Ecohydrology, in press
7. Veatch, W, P.D. Brooks, *J. Gustafson, N. P. Molotch, Quantifying the effects of forest canopy cover on net snow accumulation at a continental, mid-latitude site, Valles Caldera National Preserve, NM, USA, Ecohydrology, Vol. 2, doi: 10.1002/eco.45, 2009.
8. Molotch, N.P., Reconstructing snow water equivalent in the Rio Grande headwaters using remotely sensed snow cover data and a spatially distributed snowmelt model, Hydrological Processes, Vol. 23, doi: 10.1002/hyp.7206, 2009.
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10. Durand, M., N.P. Molotch, and S. Margulis, A bayesian approach to snow water equivalent reconstruction, Journal of Geophysical Research, 113, doi:10.1029/2008JD009894, 2008.
11. Molotch, N.P., P.D. Brooks, S.P. Burns, M. Litvak, J.R. McConnell, R.K. Monson, and *K. Musselman, Ecohydrological controls on snowmelt partitioning in mixed-conifer sub-alpine forests,

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12. Veatch, W, P.D. Brooks, *J. Gustafson, N. P. Molotch, Quantifying the effects of forest canopy cover on net snow accumulation at a continental, mid-latitude site, Valles Caldera National Preserve, NM, USA, Ecohydrology, Vol. 2, doi: 10.1002/eco.45, 2009.
13. Molotch, N.P., Reconstructing snow water equivalent in the Rio Grande headwaters using remotely sensed snow cover data and a spatially distributed snowmelt model, Hydrological Processes, Vol. 23, doi: 10.1002/hyp.7206, 2009.
14. Molotch, N.P., T. Meixner, and M.W. Williams, Estimating stream chemistry during the snowmelt pulse using a spatially distributed, coupled snowmelt and hydrochemical modeling approach, Water Resources Research, Vol. 44, doi:10.1029/2007WR006587, 2008.
15. Durand, M., N.P. Molotch, and S. Margulis, A bayesian approach to snow water equivalent reconstruction, Journal of Geophysical Research, 113, doi:10.1029/2008JD009894, 2008.
16. Molotch, N.P., (2009), Reconstructing snow water equivalent in the Rio Grande headwaters using remotely sensed snow cover data and a spatially distributed snowmelt model, Hydrological Processes, Vol. 23, doi: 10.1002/hyp.7206.
17. Molotch, N.P., P.D. Brooks, S.P. Burns, M. Litvak, J.R. McConnell, R.K. Monson, and K.Musselman (2009), Ecohydrological controls on snowmelt partitioning in mixed-conifer sub-alpine forests, Ecohydrology, Vol. 2, doi: 10.1002/eco.48.

Project Objectives
The objectives of this project is to develop a new method of snowfall estimation using an Ensemble Kalman Smoother to assimilate new remotely sensed snow measurement capabilities into physically based mass and energy balance models. To meet this objective three research questions have guided our activities:

1. Do snow cover depletion patterns during the snowmelt season contain information with respect to the spatial distribution of snow accumulation during the winter season?

2. To what extent can the snow measurement clusters and proposed snowfall reconstruction technique improve basin-scale estimates of snowfall relative to current operational techniques? Can snowfall reconstructions from relatively short time periods (i.e. 3 years) improve real-time estimates of snowfall?

3. How does local-scale topography and landcover influence snow distribution and total water storage in the mountain snowpack? How consistent are local-scale snow distribution patterns from storm to storm throughout the accumulation season?

To address these three questions we have devised a work plan that relies on manual and automated ground based snow observations, remote sensing of snow cover, and modeling. These activities are summarized below.

Field Activities & Findings
In an effort to understand inter-storm variability in snow accumulation and to develop a robust ground-truth data set for our modeling activities we conducted a total of 24 watershed-scale snow surveys during this project. Survey measurements of snow depth, snow density, and physical snow properties were conducted at two sites in the Southern Sierra Nevada (i.e. the Wolverton and Tokopah Basins of Sequoia National Park), at three sites in the Eastern Sierra (i.e. Mammoth Pass, Virginia Lakes Ridge, and Rock Creek), and at two sites in the Central Sierra Nevada (i.e. at Gin Flat and Ostrander of Yosemite National Park). The sites represent both alpine and sub-alpine environments ranging in elevation from 7,500 to 10,000 feet above sea level and covering one to 19 km^2 in aerial extent. These surveys were conducted to obtain a solid ground-truth data to support the modeling activities. In this regard, the snow surveys were timed to coincide with seasonal accumulation, maximum accumulation, and the snowmelt season such that

our model performance can be evaluated during different snowpack conditions. Each survey required a team of five people working for 3 – 5 days, involving undergraduate and graduate students from UCLA, UCSB, and UC Merced. On average, surveyors collected over 400 spatially distributed snow depth measurements and extensive information from three snow pits during each survey, resulting in a seasonal total of over 2000 snow depth measurements and 24 extensive snow pit observations. The total number of measurements acquired for the project exceeded 4000 snow depth measurements and over 50 detailed snow pit observations.

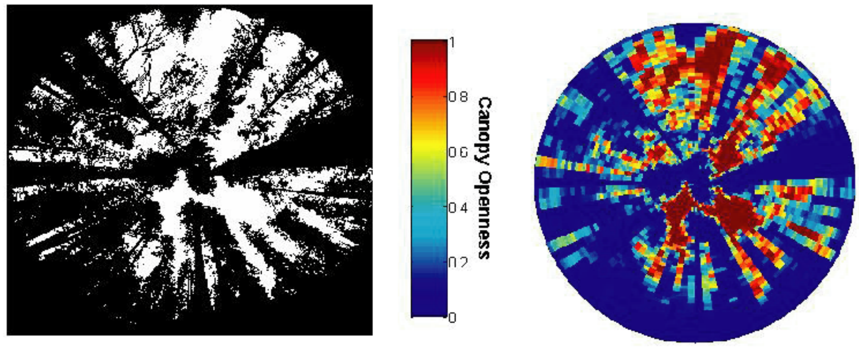

Figure 1. Hemispherical photograph looking skyward underneath an ultra-sonic snow depth sensor within an ecohydrologic instrument cluster (left). Estimates of canopy openness derived from the Gap Light Analyzer software corresponding to the image at right.

In addition to the manual measurements described above we have also altered our work plan to dovetail with activities ongoing at the Southern Sierra Critical Zone Observatory (SS-CZO) – a large NSF initiative lead by collaborators at UC Merced. In this regard, we have co-lead the development of a network of hydrologic instrument clusters in the Wolverton Basin which is a pilot site for the SS-CZO. These instruments provide hourly observations of snow depth, soil moisture, sap flow, and atmospheric conditions to be used to validate the extrapolation of our forcing data and model parameters. These data also provide important information regarding the effect of vegetation on snowpack properties, which has become a focus of our activities in the sub-alpine zone (see below).

Modeling Activities & Findings

We have further developed our plot-scale snowpack modeling activities and improved representation of snow-vegetation interactions within our modeling scheme. Year 1 activities indicated that our snowpack modeling in the sub-alpine zone needed to be improved with respect to representation of snow-vegetation interactions. Thus, we have altered our work plan slightly to include the physically based SNOWPACK model, which we are now applying to our study domain in Sequoia National Park. In this regard we have forced the model with both measured forcings and with model generated forcings at each of the twenty-four instrument arrays for water years 2007 and 2008. Through this experiment we are able to reveal the dependence of model accuracy on uncertainty in the model forcings and therefore we are able to identify areas where improvements to our model forcings are needed. Emphasis has been placed on the parameterization of sub-canopy solar and longwave radiation and associated controls of canopy structure on energy balance dynamics. The results of this work, which were presented at the Fall 2009 AGU meeting (see Musselman et al., 2009) and soon to be submitted for peer-review publication, indicate that detailed indices of canopy structure, derived from hemispherical photographs (Figure 1), can explain variability in snow accumulation and snowmelt. Furthermore, we show that these indices can be used to improve energy balance forcings and therefore improve simulations of snowmelt at the basin-scale.

In addition to these activities, we have also continued to develop our technique to utilize the detailed snowmelt modeling described above to disaggregate coarse-scale gridded precipitation products to high spatial resolution. This disaggregation scheme uses a Bayesian data assimilation method similar to the Ensemble Kalman Filter (EnKF) in a

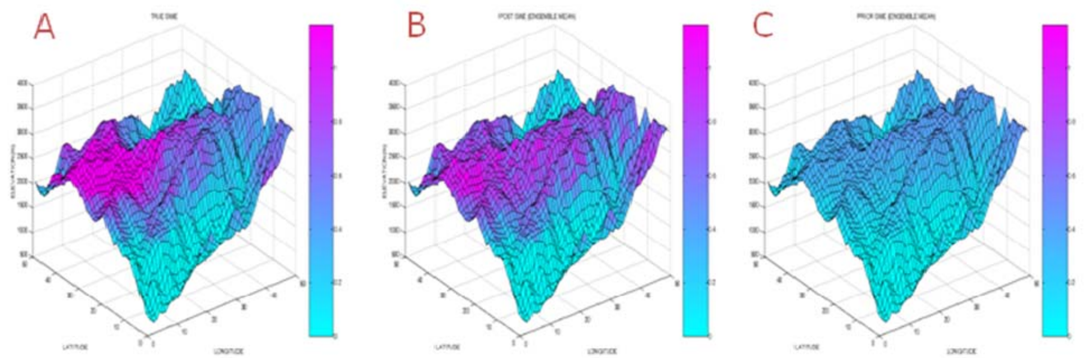

Figure 2. Synthetic experiment over 25-25 km domain in Sequoia National Park showing "true" snow water equivalent (A), posterior snow water equivalent after assimilation of MODIS snow cover images (b), and prior snow water equivalent from the open loop simulation (c). Note the clear improvement in SWE estimation with the inclusion of the MODIS data as evident in the closer match of B to A relative to C to A.

retrospective analysis step similar to the snow water equivalent (SWE) reconstruction model developed by PI Molotch. These disaggregation weights effectively downscale coarse-resolution estimates of precipitation to the finer resolution needed for complex topography. Preliminary synthetic tests conducted under this project (Durand et al., 2008) were developed for the study sites of the NASA Cold Lands Processes Experiment, allowing us to leverage unprecedented forcing and evaluation data. We have built on these results by testing the method at our intensive study sites in Sequoia National Park where we have additional ground truth data associated with the SS-CZO. These tests illustrate that assimilation of satellite-based snow cover depletion data into a distributed land-surface model improves our ability to distribute precipitation and snow water equivalent across our study domain (Figure 2). These results illustrate the utility of our technique distributing point measurements of precipitation across the landscape. Hence, the contribution to the broader community is considerable in that relatively crude techniques are currently used by the community to estimate precipitation in mountainous environments. These results were presented at the fall 2009 AGU meeting in San Francisco (see Girotto et al., 2009) and are being prepared for peer-review publication.

Award No. G09AC0001 Monitoring and Forecasting Climate, Water and Land Use for Food Production in the Developing World

Basic Information

Title:	Award No. G09AC0001 Monitoring and Forecasting Climate, Water and Land Use for Food Production in the Developing World
Project Number:	2008CA262S
Start Date:	10/1/2008
End Date:	9/30/2013
Funding Source:	Supplemental
Congressional District:	
Research Category:	Not Applicable
Focus Category:	None, None, None
Descriptors:	
Principal Investigators:	

Publications

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The Department of Geography at UCSB has a program of cooperative activities with the U.S. Geological Survey in support of the Famine Early Warning Systems Network (FEWS NET). These activities focus on the application and development of techniques for monitoring the physical variables governing crop growth, such as the timing and amount of precipitation, evapotranspiration and temperature, along with human-related factors such as cropped area, agricultural inputs, and economic indicators. We combine university-based research in the modeling, monitoring and analysis of remotely sensed estimates of environmental variables with science advisory, training, and development activities in Africa and Central America. This project brings together field scientists from Africa and Central America with research scientists at the University of California, Santa Barbara, in a single team of the UC Center for Water Resources, assembled to take on the activities needed to deal with threats to food security in the developing world.

The combination of natural variability, climate change, and the current global food crisis makes the monitoring of climate, water, and land resources for food production especially critical. Each year over 200 million people in sub-Saharan Africa face undernourishment, accounting for nearly 32 percent of the population of this region according to the Food and Agriculture Organization (FAO, 2006). This region is the only part of the world where the percentage of undernourished people has remained steady over the last 30 years. Climate, water, land use, and food supply are inextricably intertwined in the developing world where irrigation is limited and crop health is primarily dependent on the available rainfall. Monitoring of rainfall and runoff provides insight into potential crop yield reduction due to drought, as well as identifying locations which may have seen crop loss due to flood inundation. In addition to the impacts of these disasters on food supply is the effect these extremes have on the entire economy of developing countries (Kreimer and Arnold, 2000). The economic effects of hydro-climatic extremes in developing countries can easily be equivalent in cost to war (Kates, 2000).

Early detection of climate-related stress or changes in human behavior can forecast and make possible the mitigation of the impacts of below-average food production. Alerting decision-makers at agencies such as the US Agency for International Development, US Department of Agriculture, State Department, World Food Program, the Food and Agriculture Organization, and affected national governments can help mobilize action for relief efforts, management of stocks of food reserves, and other measures to reduce the harm to vulnerable populations. Development of monitoring tools to track precipitation, soil water, evapotranspiration, crop development, cropped area and other physical parameters can, individually or collectively, indicate the potential for crisis. The earlier these events can be effectively diagnosed and communicated to decision-makers, the sooner measures can be taken to reduce their impacts, saving lives and livelihoods, and protecting hard-won gains in the economic growth of developing countries.

The University’s strengths in statistical climatology, hydrology, GIS, remote sensing, and geostatistics match up well with the goals and priorities of FEWS NET. The university can use these strengths to improve the scientific research, capacity building, and applications of the USGS component of FEWS NET. Both on-campus and off-campus activities (in FEWS NET countries) are proposed.

The university's scientific focus will be on estimating food production, with emphasis on monitoring and forecasting the natural and human inputs to food production. Basic research will address improved monitoring of rainfall, crop modeling, and cropped area estimates in FEWS NET countries. Better techniques, algorithms, and modeling applications, involving exploitation of remote sensing and other geospatial data, will emerge. Uncertainty associated with monitoring products and seasonal forecasts will be made clear to users, and the spatial data infrastructure underpinning the analyses will strengthened.

1. GeoWRSI

The GeoWRSI tool is a program developed by our southern Africa field scientist. This multi-faceted program was originally designed to allow users to run their own WRSI estimates. Based on initial positive response and some feedback the scope is developing into a end-to-end program which will take satellite based rainfall fields, allow users to input their own station data, update fields of evapotranspiration or crop coefficient, and run scenarios for the remainder of the season. This work will require extensive programming and debugging efforts, but the end result is a valuable stand-alone program allowing various agencies to create products that best simulate their local conditions based on additional inputs. Products that allow users to input their own data (station or field measurements), manipulate model drivers (start-of-season, crop coefficient, length of growing period, etc.), or run simulations (i.e. mean rainfall for remainder of season, 20th percentile rainfall for remainder of season, etc.) are the type of integrated approach that much of the research in this proposal seeks to produce.

2. Temperature and photoperiod inputs to yield estimation

The previous section shows how yield modeling is principally based on simulating the crop water balance through the growing season, as moisture deficits in many crops explain more of the observed inter- and intra- seasonal variability in yield than does temperature. But 21st century climate forecasts simulate temperature change much more reliably than precipitation variability, and the relationship between the two is likely to become more important in terms of crop yields.

The effort described here will improve the WRSI model for monitoring seasonal crop development and yield by incorporating temperature and photoperiod as climate inputs, which will increase model accuracy, as these are also important factors in certain crop development. For example, Thompson (1968) found the single best weather variable for estimating corn yields in the Midwest U.S. to be an accumulation of the daily maximum temperatures above 32 degrees C in July and August. In general, he found that state average corn yields decreased about 63 kg/ha for each 5.5 degrees C accumulated above 32 degrees C. This period usually covers the time of corn silkening, an especially critical period for determining the number of kernels on the ear. (*Crop Reactions to Water and Temperature Stresses in Humid, Temperate Climates*, *1983*). Likewise, yield for Africa's second most important crop after maize, sorghum, is not simply a function of total seasonal rainfall, even where rainfall is the main limiting factor. The most important physiological adaptation mechanism of sorghum to climate variability, the triggering of flowering by day length signals (photoperiodism), synchronizes the final development stages of the plant with the end of the rainy season. *(Kouressy et al. 2007).* By adding crop-specific temperature thresholds and photoperiod characteristics to the current moisture-deficit simulation, the WRSI model will be an even more effective tool for monitoring crop yields throughout the season

3. Crop area estimation

Tools such as the GeoWRSI focus on the estimation of crop yield. While variability in crop yield is a large source of uncertainty in the estimate of food production, the amount of cropped area is also carries large uncertainty, especially in areas where changes in land tenure and expanding or moving populations have resulted in sudden changes in cropped area. Traditional cropped area estimates have resulted from statistical sampling through either field visits or farmer surveys. This proposal plans to improve on these estimates through the use of satellite imagery.

An example of one strategy to improve on this has been exhibited for a portion of Ethiopia (Husak et al, 2007). This study used interpreted high resolution satellite data, combined with physical information such as slope, elevation and rainfall, along with interpreted variables like landcover to estimate the cropped area in select districts. In this modeling, the interpreted high resolution imagery serves as a surrogate for field visits. High resolution image interpretation has been shown to be reasonably accurate in identifying cropped area from non-crop for studies in Niger. Using this data the model is based on tens of thousands of site “visits”, far beyond a typical field visit. Another advantage of these estimates is that the uncertainty in the model is defined, allowing for an approximate range of values which the cropped area falls within.

Studies like the one performed in Ethiopia can be replicated in other locations to ascertain cropped area for countries of interest. The statistical model needs to be developed for each country to account for local relationships between physical variables and cropped area, but the general methodology should remain consistent. Additionally, this proposal will look to include additional variables which may provide more explanatory power in defining cropped area.

4. Improved rainfall estimates

Integration of data from a variety of sources can result in a product that exploits the positive characteristics of all the input datasets. This is especially true for precipitation where satellite derived estimates can be merged with station values to create a rainfall field that is superior to either of these sources individually. The team at UCSB has developed a series of tools and techniques that allow the analysis and integration of points and raster rainfall datasets. Many of these techniques have bee developed for specific regions or to work with specific datasets and, in many cases, they are isolated and are not in a format that is easily replicated in other regions. The work for this proposal is to integrate the existing techniques and develop new ones to create a straightforward process for the development of the most accurate possible rainfall data sets that serve as input to crop, rangeland or hydraulic models. The process would include the analysis of station data using conventional and geostatistical techniques, unbiasing satellite data using climatological means, the integration of station data with raster rainfall fields, and the creation of historical datasets in raster format. The final product is the development of a standard set of tools which can be broadly applied to many regions for local scientists to implement using available data.

Some of the work that is already done includes: high resolution (5km) cliamtological monthly means which have been temporally downscaled to create dekadal mean fields for Central America, techniques to unbias TRMM data using climatological means, integration of station data with raster rainfall. Formalizing these techniques into a suite of tools which can be universally applied is necessary to insure a widespread use and formalized methodology in the application.

This work builds on two years of this agreement as well as previous agreements which identified and built relationships with individuals and institutions in food insecure regions to facilitate the passage of information between at risk populations, decision-makers and domestic and international government agencies. Research collaborations between the USGS and the International Program at the National Center for EROS have cooperated on a wide range of projects including modeling and mapping precipitation and precipitation related fields to support drought and flood mitigation, analyzing the impacts of sea-surface temperatures on global atmospheric circulation and rainfall, and estimating crop area in African countries. These activities are carried out by a team of researchers, graduate students and technicians at UCSB as well as field scientists stationed in Africa and Central America.

Irrigating citrus with reclaimed municipal wastewater.

Basic Information

Title:	Irrigating citrus with reclaimed municipal wastewater.
Project Number:	2010CA263B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	44
Research Category:	Water Quality
Focus Category:	Wastewater, Irrigation, None
Descriptors:	None
Principal Investigators:	Christopher Amrhein

Publications

1. Western Society of Soil Science and Western Society of Crop Science Joint Annual Meetings with the Western National Cooperative Soil Survey June 21-24, 2010 Las Vegas, NV Escalera, Julie, Dennise Jenkins. 2010 Using Reclaimed Water for Irrigation
2. ASA, CSS, SSSA 2010 Annual Meeting (Oct. 31 - Nov. 4, 2010) Long Beach, CA. Jenkins, Dennise, Julie Escalera. 2010 "Using Reclaimed Water for Irrigation."

Drought and water shortages are becoming an unavoidable crisis in arid regions. As a result, cities are considering switching agricultural irrigation over to reclaimed water to free up good quality ground water for municipal uses. However, reclaimed water can decrease hydraulic conductivity in the soil because it contains a high concentration of dissolved salts and sodium. Sodium reduces hydraulic conductivity by swelling and dispersing clay particles in the soil thus reducing the water-conducting pores. Reduced water infiltration may cause ponding, root rot and damage to crops. Furthermore, high concentration of boron found in recycled water can lead to toxicity in plants like citrus.

The purpose of these laboratory experiments was to determine the effect of reclaimed water on hydraulic conductivity and changes to the boron concentration in soils cropped to citrus. Results show that reclaimed water can significantly decrease hydraulic conductivity on soils found in Riverside orange orchards. Soils with horizons of clay accumulation showed a greater reduction in hydraulic conductivity and higher boron adsorption. This suggests that farmers might have to change their irrigation practices if they are forced to use reclaimed water for irrigation.

Problem

California just experienced the longest drought in recent history and its effects have taken a toll on the availability of drinking water for Southern California. As a result, reclaimed water is seen as a good alternative to higher quality well water. However, citrus and avocado growers are concerned that elevated concentrations of boron, salts, and surfactants in reclaimed water could adversely affect their orchards. Reclaimed water can decrease saturated hydraulic conductivity in the soil due to it’s higher concentration of dissolved salts and sodium. Sodium reduces hydraulic conductivity by swelling and dispersing clay particles in the soil thus reducing the water-conducting pores. Reduced water infiltration may cause ponding, root rot, and damage to crops.

The scientific literature contains conflicting reports on the “permissible limits of boron” recommended for “sensitive crops” such as citrus and avocadoes. The current safety guidelines, published by the California State Water Resources Control Board in

1984, state that a boron concentration of 0.7 mg/L in irrigation water is safe for all crops in California (Pettygrove and Asano, 1984). This guideline is more than double the "permissible limits of boron" reported by the U.S. Salinity Laboratory which recommended that "sensitive crops," which include citrus and avocado, should not be irrigated with water containing more than 0.33 mg/L boron (USSL Staff, 1954, page 81). Upon further investigation, it appears that the 1984 California guidelines mistakenly adopted limits for boron in **irrigation water** that were originally reported for the boron limits in **soil water** (Eaton, 1944; Pettygrove and Asano, 1984; Maas, 1984).

The purpose of these laboratory experiments was to determine the affect of reclaimed water on saturated hydraulic conductivity and re-evaluate the guidelines for irrigation with respect to boron concentrations in soils cropped to citrus (Riverside, CA).

Research Objectives

The objective of these experiments is to determine the affect of reclaimed water on saturated hydraulic conductivity and re-evaluate the guidelines for irrigation with respect to boron concentrations in soils cropped to citrus (Riverside, CA).

Particular attention was given to horizons of clay accumulation since they are expected to show a greater reduction in hydraulic conductivity and boron adsorption. The surface horizon and a deeper horizon were selected for evaluation. Blending water, mixing lower salinity water with reclaimed water is a common practice to improve water quality. Therefore, a blend of reclaimed water and the control was included as a treatment in this experiment.

Methodology

Evaluating the toxicity of reclaimed water to citrus is difficult in a short-term study because of the adsorption capacity of soils. Irrigation of a mature orchard with reclaimed water would require several years before the adsorption capacity of the soil is satisfied and equilibrium conditions are approached. A way to overcome the adsorption problem is to grow trees in sand tanks using nutrient solutions. However, there is concern that high calcium concentrations in the nutrient solutions will reduce the toxicity of the B because of calcium-borate complexes (Steve Grattan, U.C. Davis, personal communication). Also, a high concentration of calcium affects membrane integrity and this is a factor affecting specific ion toxicity (Grattan and Grieve, 1999). Thus, we proposed a two prong approach to evaluating B-toxicity to citrus and the effects of Na and surfactants on soil permeability.

We are currently using laboratory experiments to determine B-adsorption constants and the effects of the reclaimed water on hydraulic conductivity parameters of the citrus soils in Riverside County. Hydraulic conductivity studies were done with repacked soil columns in the lab and with portable parameters in the field.

These measurements will be used as input to the soil/water/plant models SWS and UNSATCHEM, available from the USDA Salinity Laboratory (Suarez and Simunek, 1997; Suarez and Vaughan, 2001; Suarez, 2005)). This model includes variations in soil properties with depth, and changes in soil permeability due to changes in SAR over the growing season. Boron adsorption is modeled using the constant capacitance model (Goldberg et al., 2000).

The sample location was a mature orange grove located in the Riverside Greenbelt area, GPS coordinates 33^{o} 53’ 30” N, 117^{o} 25’ 59” W. The soil found in this orchard was representative of other soils located in the Greenbelt area and is classified as an Arlington loam. Moisture temperature regime is xeric with dry hot summers and cool winters.

Site locations were selected with a random sample model. EPA hand auger soil sampling procedures were implemented using a continuous sample method. The sample site was located in the irrigation furrow approximately 2 meters away from the base of the tree. Soil was collected with a 3 inch metal hand auger. Soil sampling through the full soil profile is essential because of the subsoil chemical and physical properties are expected to be the biggest problem. After collection, the soil was air dried at 120 ^{o}F. Then, the soil was hand sieved through a 2 mm sieve to remove gravel from the fine earth fraction. The surface horizon and a deeper horizon were selected for analysis; 0-20 cm and 40-60 cm. Soil texture was determined in the lab with Particle Size Analysis. Bulk density and organic matter content were determined in the lab. See soil data chart.

Soil Data Chart					
Depth (cm)	% Clay	% Silt	% Sand	Column g/cm^3	% Organic Matter
0-20	23	33	44	1.54	2.0
40-60	27	42	31	1.61	1.5

The soil was packed in 15 cm PVC columns with a 5 cm inside diameter. One end of the column was covered with cotton gauze and the edges of the gauze were taped to reduce evaporative loss. Each column was filled with 200 g of soil in 50 g increments. Soil was packed to approximately the same density by using a drop-compactor. Initial hydraulic conductivity rates were measured using Gage Canal water. Because Gage Canal water has been used to water these orchards for over 130 years, Gage Canal water was used as a control.

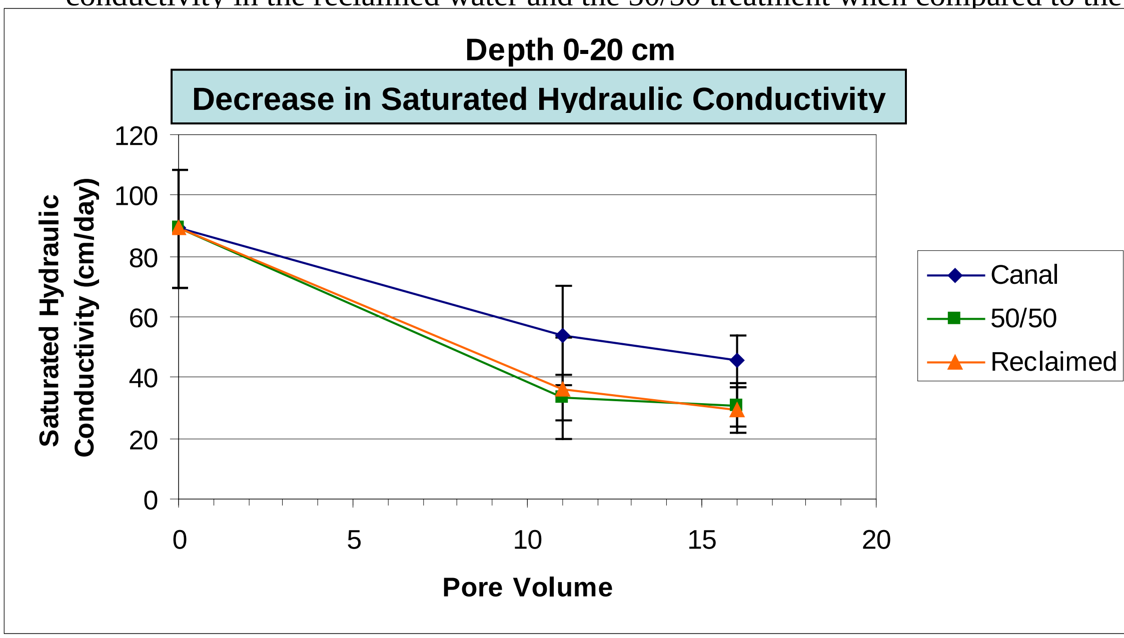
Saturated hydraulic conductivity (Ksat) was determined using Darcy's Law with a constant-head model. Columns were allowed to reach a steady state before rates were measured. Plant available boron concentration was determined by hot water extraction. Three water treatments were selected. See chart attached. Water was applied in 100-200 mL increments. To simulate field conditions, columns were allowed to dry between applications of water.

Water Quality	**Gage Canal (Control)**	**50/50 (reclaimed/control)**	**Reclaimed**
EC (mS/cm)	**0.58**	**0.77**	**0.90**
pH	**7.9**	**7.9**	**7.6**
Alk (mg/L $CaCO_3$)	**165**	**177**	**177**
SAR	**0.60**	**1.3**	**1.8**

<u>Principle Findings (Preliminary)</u>

In the deeper horizon, depth 40-60 cm, there was no significant change in hydraulic conductivity. In this depth all treatments reduced hydraulic conductivity and the control was not statistically different from the reclaimed water and 50/50 treatment. See attached graph.

In the surface horizon, 0-20 cm, there was a significant difference in hydraulic conductivity in the reclaimed water and the 50/50 treatment when compared to the



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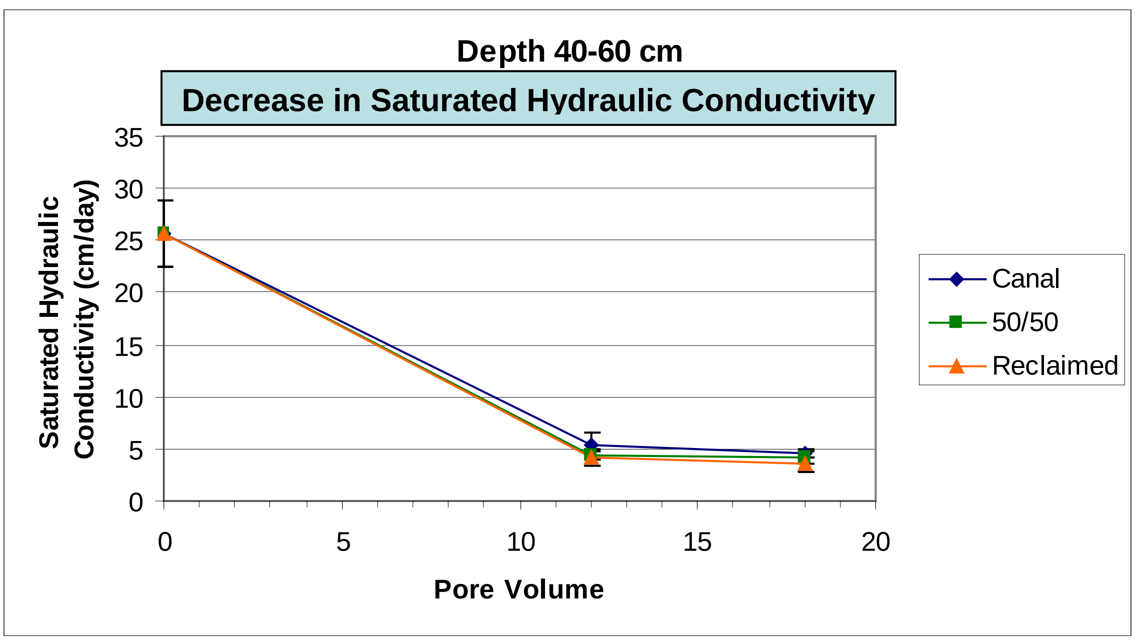
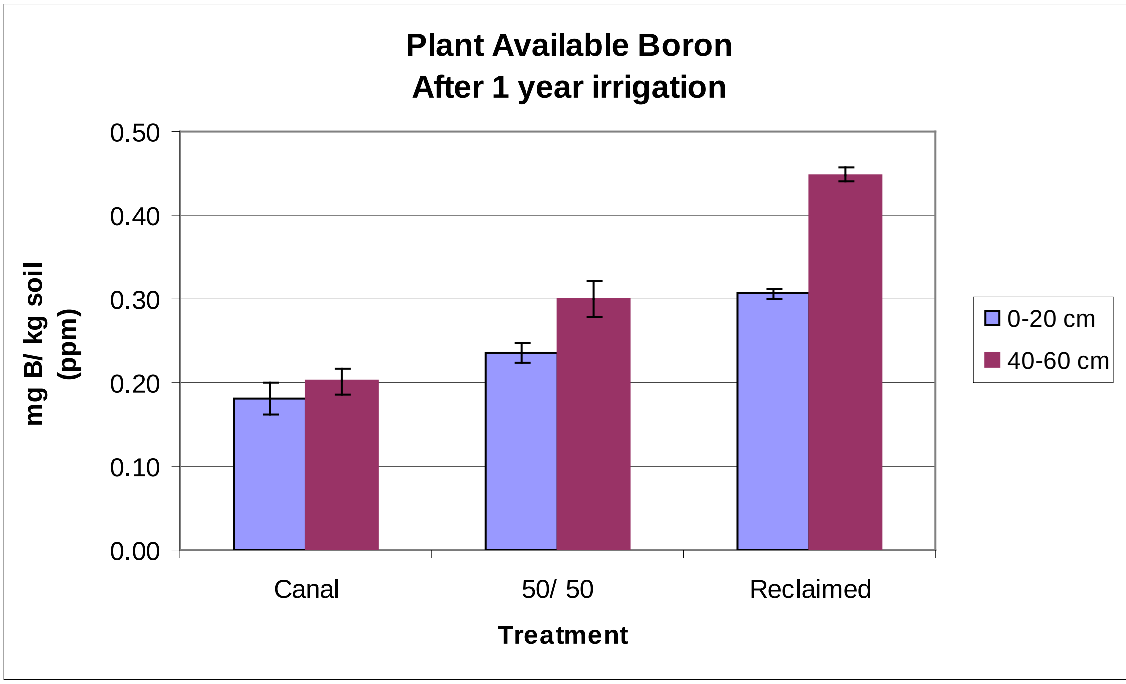


After 1 Year Irrigation



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water control. The lower horizon, depth 40-60 cm, showed the largest increase (123%) in plant available boron concentrations in the soil for the reclaimed water treatment. Although still under the toxic threshold for citrus (0.7 ppm boron) after one year of irrigation, the reclaimed water results suggests a possible boron toxicity may occur during the second year of irrigation. A multi-year irrigation study is in progress.

The surface horizon, depth 0-20 cm, showed the greatest overall reduction in saturated hydraulic conductivity for the reclaimed and 50/50 treatment when compared to the control. All treatments showed a significant decrease in saturated hydraulic conductivity which may be due to formation of vesicular pores inside the columns. The results based on the surface horizon data suggests that farmers might have to change their irrigation practices or add gypsum to the soil if they use reclaimed water for irrigation.

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An Advisory Service for Optimum Irrigation Scheduling in California

Basic Information

Title:	An Advisory Service for Optimum Irrigation Scheduling in California
Project Number:	2010CA264B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	44
Research Category:	Climate and Hydrologic Processes
Focus Category:	Irrigation, None, None
Descriptors:	None
Principal Investigators:	Allan Fulton

Publication

1. Possible publications anticipated from this project include submission of an article to the Journal of Irrigation Science offering an assessment of this Online Irrigation Scheduling tool. Specifically, the article may address the validity of the irrigation schedules recommended by the IMO, the suitability of this program for grower adoption, opportunities for improvement, and assessment of the accuracy of the economic model which predicts yield and revenue losses associated with deficit irrigation of perennial orchard crops in California.

This NIWR Funding was a supplemental grant used in conjunction with funding from the UC Water Resources Center Prosser Trust and a USDA CIG grant. The NIWR funding was for one year and totaled $25,600 and contributed approximately 10 percent of the total support for the project titled **"An Advisory Service for Optimum Irrigation Scheduling in California"** that was conducted in the 2009 and 2010 seasons.

During this project, we refined the software in the Irrigation Management On-line (IMO) Scheduling program for use in California. Specifically, the ability to automatically upload reference evapotranspiration (ETo) for short canopies from the California Irrigation Management Information System (CIMIS) was added to the IMO. The On-line Scheduling program can be accessed at the url: <(http://oiso.bioe.orst.edu/RealtimeIrrigationSchedule/index.aspx>. In addition, the crop coefficient data base was expanded to include all known crop coefficients from California, and the software was modified to include high frequency irrigation systems (i.e. drip and micro-sprinkler) for scheduling. Based on feedback from grower-cooperators in 2010, we developed new, simpler software at the request of growers participating in the project. Blake Sanden (Kern County), Allan Fulton (Tehama County), and Dan Munk developed active field research projects to validate the IMO program, and they developed excellent cooperation with growers to test the program. Until the IMO program was introduced into California production systems during the past two years, the program focused primarily on furrow, flood, center pivot, and hand-line and wheel-line sprinkler systems in agronomic and vegetable crops. Therefore, the UCCE farm advisors worked closely with OSU personnel to design and expand the software to apply to high frequency irrigation systems and orchard crops. They served as intermediaries between the grower-cooperators and the OSU program developers to provide feedback on how to improve the scheduling model. The farm advisors conducted several meetings with growers to train them on how to use the IMO and to gain feedback on the growers' perception about how to improve the model.

At UC Davis, we accumulated a data base of crop coefficients for expansion of the IMO into California. Using Excel software, we developed an irrigation scheduling model that accounts for water and salinity stress and during the first year of the experiment, but we were unable to find data to test the model from any source including the USDA Salinity Lab. Because of the lack of field data to test the model, we did not modify the IMO software to use the water and salinity stress model. We looked for sources of field data on interactions between salinity and water stress, but to our knowledge, none is available. However, we were able to enlist the support of the Biosaline Research Center in Dubai. Because of water and salinity stress problems in the Middle East, they have agreed to set up experimentation to validate the model. This year, they initiated field research to begin the verification process, and we will refine the experiments to validate the model in following years.

Irrigation scheduling of orchard crops is considerably more difficult than field crops because the water requirements are less well known and they often produce better in the long-term when moderate water stress is applied at certain times of the season. We chose to use almond, walnut, and prune orchards as our study crops in this project. Almond is a major water using crop throughout the Central Valley of California, and the University of California has a strong research program related to quantifying water stress in almonds. Walnut and prune are also major crops in the northern Sacramento Valley (Tehama County) that have been supported with field research quantifying the effects of deficit irrigation. The UCCE Farm Advisors worked on field studies that related midday stem water potential readings and soil moisture monitoring for use in the Bayesian decision model used in IMO. We monitored evapotranspiration, soil moisture, and plant-based stress in each county in addition to working with growers.

There was been excellent cooperation between the Oregon State and UC Davis personnel. We emphasized irrigation scheduling of almond, walnut, and prune orchards with micro-sprinkler and drip irrigation systems because it comprises a growing part of California that differs from earlier work done in Oregon. The revised software and what we learned was a good first effort to expand IMO into California. In future years, our research group will move on to other crops to continue refining crop coefficients and water management. A detailed summary of accomplishments is provided in the following sections.

INTRODUCTION TO RESEARCH PROGRAM:

The potential for using computers to schedule irrigation has been recognized for at least 40 years (Jensen, 1969; Jensen et al., 1970). As of 2008, however, less than 2% of irrigated farms use computer simulation models to schedule irrigation (USDA, 2009). Yet, the demand for water has increased for some time. Still, the 'Condition of crop' and 'Feel of soil' are still the dominant methods for deciding when to irrigate (Table 1).

Over the past decade, several new irrigation schedulers were developed and new ones are under development. In addition, several new technologies present an opportunity as more robust tools for improving efficiency of irrigation. The increasing demand for water will necessitate that the next generation consider a broader range of management options.

Table 1. Methods Used in Deciding When to Irrigate (USDA, 1995, 1999, 2004, 2009)

Reported Method	***1988***	***1994***	***1998***	***2003***	***2008***
All farms	223,943	198,115	223,932	210,106	206,834
Any method	93.6%	94.9%	98.6%	100.0%	100.0%
Condition of crop	71.9%	68.2%	72.9%	79.4%	77.7%
Feel of soil	36.1%	39.5%	40.4%	34.8%	42.6%
Personal calendar schedule	15.4%	16.7%	18.0%	19.3%	25.1%
Scheduled by water delivery organization	10.6%	14.1%	10.1%	12.5%	11.8%
Soil moisture sensing device	7.5%	9.6%	8.0%	6.8%	8.6%
Reports on daily crop-water evapotranspiration	4.3%	4.4%	4.8%	7.2%	9.1%
Commercial or government scheduling service	4.5%	4.9%	3.2%	6.4%	8.0%
When neighbors begin to irrigate	NA	NA	NA	6.7%	6.9%
Computer simulation models	NA	2.3%	1.0%	0.6%	1.4%
Plant moisture sensing device	NA	NA	NA	1.5%	1.7%
Other	5.4%	8.7%	7.0%	8.9%	8.7%

Scientific irrigation scheduling is defined as the process of determining when and how much to irrigate (Cuenca, 1989) based on scientific principles. Conventional irrigation practices are predicated to maximize production. The National Engineering Handbook (NRCS, 1997) recommends that soil moisture be maintained above a management-defined level based on crop stress. Similarly, FAO 24 (Doorenbos and Pruitt, 1992) defines irrigation water requirements in terms of full production potential. Both of these recommendations are based on an underlying biological objective of maximizing production, and the soil moisture status tends to weigh heavily on the decision process. Irrigation Optimization is a different task which seeks to allocate water according to one or more goals rather than simply maximizing production (English et al., 2002). According to Martin et al. (1990), optimizing an irrigation schedule has the following goals:

- maximizing net return,
- minimizing irrigation costs,
- maximizing yield,
- optimally distributing a limited water supply,

- minimizing groundwater pollution or
- optimizing the production from a limited irrigation system capacity

Shortage of water resources was identified as the reason for crop yield losses by 63% of the USA farms that reported diminished yield (USDA 2009, Table 26). Most farms have more than one field and, when the quantity of water is limited, it often affects all fields in the farm. On the other hand, when delivery capacity is limited, the shortages may apply to individual fields. In either case, the manager must consider all of the fields and the marginal value of water in each field, which is a non-trivial task. Martin and van Brocklin (1989) demonstrated some of the complexities of multi-field scheduling by using dynamic programming to schedule irrigations for a mix of crops. Lamacq et al. (1996) used a model of farmer behavior to simulate allocation of water to a group of surface irrigated fields using a network of irrigation ditches and demonstrated that decision-making must occur at the whole farm level. Bernardo (1987) used a whole farm simulation to demonstrate how, for center pivots, improved labor practices, and deficit irrigation were important adjustments for dealing with reduced water supplies.

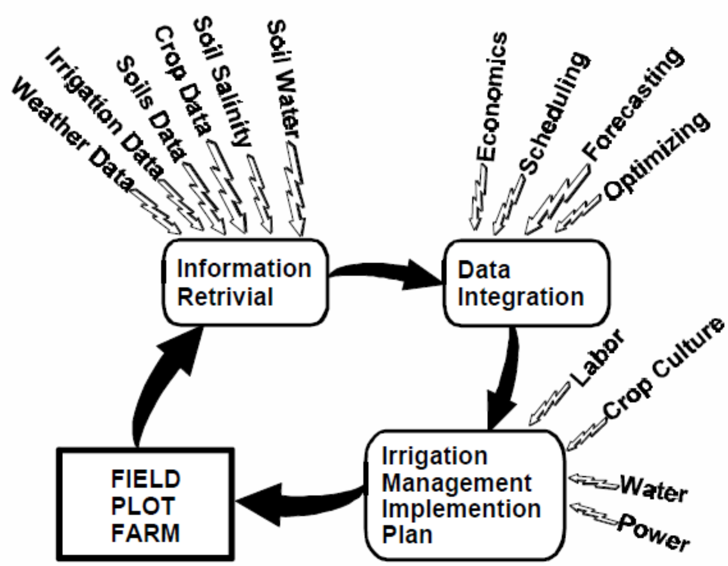
Deficit Irrigation (DI) has been demonstrated as an optimal way to maximize net returns from water and has also been demonstrated as an effective irrigation strategy when water supplies are limited (English, 1990; English and Raja, 1996). Fereres and Soriano (2006) and Geerts and Raes (2009) have reviewed the appropriate use of DI for a variety of crops. Methods for implementing DI include delaying irrigation, cancelling certain events, partial root zone drying, and reduced set times or application rates. These last two options present an important challenge for irrigation scheduling because irrigation efficiency is linked to irrigation intensity. This relationship means that the efficiency estimated at design time cannot be used to estimate application depths in water balance calculations; instead, efficiency must be simulated. The feasibility of DI also has a strong dependence on irrigation system performance, particularly on the low quarter efficiency (Rodrigues and Pereira, 2009).

DI strategies also have implications for the accuracy of the irrigation scheduler's calculations. The NRCS National Engineering Handbook recommends that "an irrigation scheduling tool needs only be accurate enough to make the decision when and how much to irrigate" (NRCS, 1997 p. 9-22). When implementing a deficit schedule, irrigators can eliminate any potential crop yield or net return benefit through errors in timing or application amounts (Dudek et al., 1981). One of the basic assumptions built into most water balance models is that an irrigation event will fill the soil to field capacity. Filling the soil minimizes the spatial variability and uncertainty about the current soil moisture status. This assumption is not valid for DI when the strategy involves only partially refilling the soil. Implementing DI requires precision irrigation that in turn requires improved spatial and temporal resolution (Sadler et al., 2005).

The sensitivity of DI to timing errors increases risk. Events beyond the manager's control, e.g. broken equipment, delivery delays, etc., make implementing DI vulnerable to events that damage yield. Despite this, Perry and Narayanamurthy (1998) have reported effective use of DI even when delivery of water supply is uncertain. Spatial non-uniformity of applied water is a significant source of risk and the variability of net returns increases when non-uniformity is considered (Bernardo, 1988). Because the necessity to reach a prescribed level of yield reduction (for net economic returns) and the increased risk, irrigation schedulers must include yield estimates with their recommendations. Hornbaker and Mapp (1988) demonstrated that daily plant models provide information for a more careful analysis of the value of timing irrigation. Raes et al. (2006) developed a coupled water balance model with a model of yield decline that uses different yield decline rates during various growth stages. The authors concluded that their model would be useful for developing irrigation strategies under deficit conditions. The papers, Raes et al. (2006), and Hornbaker & Mapp (1988) demonstrate the utility from incorporating yield estimates.

One can manage each of the risk sources (externalities, spatial variability, and excess yield reduction) through careful monitoring. Growers differ in acceptable levels of risk preference and will value scheduling recommendations differently based on their risk preference (Bosch and Eidman, 1987). Explicit consideration of growers risk preferences helps to provide a useful schedule.

The irrigation management cycle shown below is based on Figure 1 in Howell (1996). He identified 'sensor and Information Technology' as one potential area of research for irrigation scheduling and noted that not all of these sources of information have been fully utilized to facilitate irrigation decision making.



Irrigation Management Cycle (from Howell 1996)

Much has changed in information technology since 1996, and Web-based technologies have matured for information exchange. The availability of online databases for soils (NRCS, 2010), weather (NOAA, 2010), and crop information has expanded. Online delivery of data from on farm instrumentation is becoming commonplace. Perhaps the most encouraging development is the Department of Agriculture recent initiative to bring high-speed internet access to rural areas (USDA, 2010). Each of these factors presents opportunities for facilitating the "Information Retrieval" and "Data Integration" phases shown in the figure above. Building robust management information systems may lie more in the realm of computer science than in irrigation science however, dependence of irrigation scheduling on information means that developers of scheduling tools must have knowledge of both realms.

The technological advances are not necessarily improving grower confidence. In a survey of growers in the Hawkesbury-Nepean Catchment NSW, Maheshwari et al. (2003) found that while growers where interested in knowing more about scheduling they were not confident about what technologies were appropriate. In addition, when asked about soil moisture monitoring systems for paddock management, some growers said there was no use for it or considered it a waste of time.

NOAA has offered weather forecasts online for many years. However, depth of precipitation forecasts and the forecast data needed to calculate reference ET are recent products. The National Weather Service has recently started providing point forecasts available in an XML format (NOAA, 2010). Wang and Cai (2009) demonstrated that using weather forecasts could have a positive impact on water use. They found that, using seven day forecasts in conjunction with the SPAW model, growers would have lower water use during normal years and higher profit during dry years when compared to scheduling based only on current soil moisture status. Although weather data is increasingly available online, not all weather networks are providing data in forms readily useable by web based applications. For example, the Agricultural Water Conservation Clearinghouse has a list of weather stations and ET networks (Agricultural Water Conservation Clearinghouse, 2010). Of the 14 networks listed there, only the CIMIS network provides weather data in an XML format, which is an easier format for data transfer and use in the IMO. Nearly all of the networks (including CIMIS) provide their data in a 'csv' format that is readily useable by spreadsheet applications.

Acquisition of reference evapotranspiration (ETo) and crop coefficient (Kc) data is only one part of the scheduling process. Making data easy to obtain and presenting it in clear ways is a valuable feature, but the real power of irrigation schedulers lies in the potential for using the information to drive calculations that influence management decisions. In this sense, an irrigation scheduler is also a decision support system. Mohan and Arumugam (1997) indicated that expert systems are viable and effective tools for irrigation management and stressed the need to include other aspects of irrigation management such as canal and reservoir operation. This need was also indicated by Clyma (1996) who concluded that scheduling services are not adequately integrated with other farm operations that hold greater importance than irrigation decisions. Wolfe (1990) and Woodward et al. (2008) reported the need for combining irrigation tools with crop growth models. Woodward et al. also emphasized that user participation in each step of the development process is important for success of the program.

Table 1 indicates that 'condition of the crop' is the most commonly used indicator for scheduling irrigation. This implies that an irrigation scheduler that uses plant-based measurements would be more compatible with grower's current thinking. However, scheduling via plant-based measurements is not without problems (Jones, 2004). Using plant based measurements coupled with a mechanistic model has been demonstrated to be effective (Steppe et al., 2008), but the authors point out that the lack of universal parameter values for different crops is a serious limitation at present.

Nearly every region in the western USA has a scheduling tool available and a weather network that can supply data needed to perform scheduling calculations. The tools may have varying features and the weather networks varying measurement densities but all of the tools require some effort to setup and use. Even when scheduling services are free and 'self service' there is still a cost embedded in the time required to use them. The success of irrigation scheduling applications depends on more than their accuracy, ease of use, or cost. Shearer and Vomocil (1981) described the challenges and obstacles that they faced over 25 years of promoting irrigation scheduling in Oregon. They emphasized that if irrigation services are not supported externally to the farm then the growers will stop using the service. In other words, growers are willing to use irrigation scheduling, but other farm activities are considered a better use of their time.

Two examples of successful scheduling services are the IASA in La Mancha Spain (Rodriguez et al., 2002; Manas et al., 1999; Smith and Muñoz, 2002) and the El Dorado Irrigation District in northern California (Taylor, 2009). IASA, the Irrigation Advisory Service of Albacete, provides irrigation scheduling advice and decision support to growers in the Castilla-La Mancha region of Spain and has been providing this service for more than 15 years. IASA staff visit participating farms on a weekly basis, collect information for the advisory service, and disseminate scheduling information through various mediums, and provide site-specific scheduling recommendations to the participating farms. The El Dorado Irrigation District (EID) in northern California is another example of how service can make irrigation scheduling successful. The EID uses TrueISM software (TruePoint Solutions, 2008) that was custom built for their district. Automated weather stations, permanently installed soil moisture monitoring sites, and regular visits by the EID staff all reduce the effort required for the grower. The service has been operating long enough to establish accurate system characterizations and positive relationships with the growers. The El Dorado program originated nearly three decades ago, and they were one of the original cooperators in the development of CIMIS. Its success, to a large extent, is related to having long-term technical support and rapport with the growers to assist in the adoption of irrigation scheduling. The District's commitment to provide staff to support the adoption of irrigation scheduling approaches and computer programs was arguably more important that the specific approaches and computer programs. The use of TruePoint illustrates that the techniques used have improved over time. Originally, EID used an extensive neutron probe monitoring network.

Both IASA and EID are providing scheduling services, that is, the irrigation schedule is produced by applying scientific principles, but the schedule is delivered to the grower as a product of the organization. In both cases, the service involves significant hands on work by the service personnel and this time investment reduces the burden on the irrigator. Additionally, a reputation for the accuracy of the service has been established over time. This model of an irrigation scheduler does have limitations, particularly the need for continued funding, however, as Shearer & Vomocil argued, it does motivate the use of irrigation scheduling.

The IMO and this project were proposed as the next generation (NG) for irrigation scheduling programs. The goal is to make the IMO an irrigation optimization tool. As such, it will provide the following features:

- *Explicit consideration of farm level constraints*. Limitations in water allocations apply to the whole farm and should be included in the analysis as such. Limitations in supply capacity can affect at the farm or field level (either demand exceeds pumping capacity or canal flow is less than ordered). Temporal limitations on both of these (e.g. midseason changes in allocation, and restrictions on delivery timing) will also be considered.
- *Conjunctive scheduling of all fields in a farm* (or management unit). Irrigators make decisions at the farm level so a scheduler will facilitate that decision process.
- *Alternative or unconventional scheduling strategies.* These strategies would include reduced adequacy, partial season irrigation, critical growth stage scheduling.
- *Full Season forecasting*. This feature will allow growers to evaluate different irrigation strategies and for planning under different water use scenarios.
- *Consideration of economic consequences*. The impact of management recommendations will be expressed in economic terms as well as agronomic terms.

The IMO will support Deficit Irrigation (DI), which includes the following features:

- *Explicit analysis of irrigation efficiency*. Implementing DI often involves manipulating irrigation intensity. Irrigation efficiency is linked to irrigation intensity and cannot be assume a priori. Successful implementation of DI is dependent on system uniformity and efficiency.
- *Estimation of yields and potential yield losses*. DI involves some level of yield reduction relative to full production potential. Furthermore, when DI is used to maximize net economic returns, yields are an explicit part of the objective function. For both of these reasons, consideration of yields is an essential part of implementing deficit irrigation strategies.
- *Consideration of irrigator's risk preferences*. DI implies an increased risk of yield loss. People have different preferences for risk and financial status of farming enterprises may limit the amount of risk they can tolerate. Therefore, analysis of risk must be explicit in the planning of deficit strategies.

In order to support the previous two items, the IMO needs greater precision in its calculations and have smaller tolerances for errors in their forecasts. This need requires that the simplifying assumptions associated with full irrigation will no longer apply. The IMO will have the following features to support increased precision:

- *Multiple types of physical measurements will be used*. Plant based, soil moisture based, atmospheric, and remote sensing measurements will all be incorporated into the calculation of the soil water balance instead of relying completely on any one source of information for scheduling decisions.
- *Schedulers will allow for quality weighting of various measurements*. Different types of measurement have different magnitudes of error or uncertainty. Further, growers have differing levels of trust associated with newer technologies. The farmers own opinion in addition to the physical evidence should be give credence when combining various measurements.
- *Schedulers will be explicit about spatial and temporal variability*. Soil physical properties, crop characteristics, and depth of applied water all vary spatially. Using deficit irrigation strategies means that schedulers will need to consider spatial variability and its affect on the variability of its recommendations. Being explicit about the variability will help the grower to visualize the range of possible outcomes from their scheduling decisions.
- *Schedulers will be explicit about the risk and uncertainty of their recommendations*. No measurement technology can give a perfect picture of field conditions and the accuracy of weather forecasts is well known. No physical model is perfect. Each of these factors introduces uncertainty that cannot necessarily be separated. Being explicit about the uncertainty will help the grower asses the verity of the recommendations.

The IMO will include information management systems.

- *Schedulers will use relevant data from online databases*. This will include weather networks, soils databases, and remote sensing data. The scheduler will handle downloading, parsing, and integration of the data into its recommendations.
- *Schedulers will be integrated with the growers own instrumentation*. Personal weather stations have been available and affordable for some time. Increasing availability of cell phone and wireless communications means that users will be able to access the data remotely. However, at present manufacturers often use proprietary or nonstandard formats for data exchange. The NG will leverage existing standards for data exchange to automate the process of extracting instrumentation data.
- *Schedulers will use weather forecasts*. The NG will use weather forecasts to improve forecasts of irrigation needs instead of relying on historical averages.
- *Schedulers will be integrated with irrigation hardware*. Providing accurate forecasts requires knowledge of previous water use. The NG will obtain this information automatically via instrumentation on the irrigation system or through the software used to control the systems.
- *Schedulers will be online applications*. The NG will deliver scheduling recommendations using more than one web based modality. These different forms will include HTML, Web Services, and interfaces appropriate for mobile devices.

The IMO will serve as part of a service provided to the grower rather than a standalone tool. It will have the following features:

- *Schedulers will have a substantial 'service' component*. As described in the previous sections, successful schedulers have done most of the time consuming work for the grower. The NG will follow this pattern in that most of the work of preparing the schedules will be done by an organization external to the farm. The service may be public or private and may include some type of fee to the grower.
- *Federal and local organizations will be involved in delivering the service*. Federal agencies will continue to provide support from irrigation scheduling and this support will be an integral part of the irrigation scheduler through either software development or research that supports irrigation scheduling.
- *Schedules will be accessed by irrigation districts and watershed organizations*. This will allow irrigation districts to better plan and manage canal networks.

This introduction attempt outlines the requirements for the next generation of irrigation schedulers, and the IMO was designed to meet these requirements. Some of the challenges that schedulers face as well as new opportunities available to them were described. These challenges were: the complexity of irrigation optimization, the requirements for and risk implications of deficit irrigation, changes in information management technology and its potential impact, and the importance of support from organizations external to the farm enterprise. The current and future features of the IMO were described.

Background on Evapotranspiration Symbols and Terms

Actual evapotranspiration (ETa) was measured in several orchards using the eddy covariance and surface renewal methods (Paw U et al., 2005; Shaw and Snyder, 2003). Note that crop coefficient (Kc) values are computed as the ratio of unstressed crop evapotranspiration (ETc) and ETo (i.e. Kc = ETc/ETo). When evapotranspiration is measured in the field, however, there is a chance that the crop is experiencing water, salinity, or other stresses that can reduce the actual crop evapotranspiration to some value lower than ETc (i.e. ETa ≤ ETc). One can estimate ETc as ETc = ETo × Kc, where Kc is a crop coefficient used to estimate unstressed crop evapotranspiration from ETo. Actual crop evapotranspiration is estimate as ETa = ETc × Ks, where Ks is a stress factor that varies from 0 when there is no transpiration to 1.0 when the crops is unstressed. Thus, one can estimate the observed actual evapotranspiration as ETa = ETo × (Kc × Ks) or ETa = ETo × Ka, where Ka = Kc × Ks is the actual crop coefficient. One of the reasons for studying stem water potential in this project was to attempt to estimate Ks, which will improve our estimates of ETa and hence the IMO program. In general, we assume that Ks = 1.0 for a well managed, well-irrigated crop; however, almonds are often stressed during the harvesting period, so Ks < 1.0 is likely during late August and early September. Since this is research in progress, we will present the coefficients to estimate ETa as Kc × Ks in this report. Eventually, we will estimate the Kc and Ks values separately.

INFORMATION TRANSFER:

Results from UC Davis

Prepared by: Richard L. Snyder, Biometeorology Specialist

At UC Davis, the model "Irrigation Scheduling, Stress and Salinity (ISSS)" to apply reference evapotranspiration (ETo) data, crop coefficients, and soil and crop information to determine irrigation schedules that account for water stress and salinity was completed and some minor revisions were made. We were unable to find an existing data set to test the model, so we made an agreement with the Biosaline Center in Dubai to conduct research that will provide the necessary data base for testing the model. The Biosaline Center is relatively new, and they are in the process of developing a research program to address salinity and stress issues in the

Middle East. Because there is little or no published research on the interaction between water and salinity stress, UCD, OSU and the Biosaline Center have entered an agreement to cooperate on a long-term study to provide the necessary information. We are currently seeking funding from Dubai and Qatar to support this long term research.

Results from the Northern Sacramento Valley

Prepared by: Allan Fulton, UCCE Farm Advisor, Tehama County

Methods

Farm Cooperators

Two years of field research and extension activities to help refine the IMO were completed. Eight commercial orchards (almonds, prunes, and walnuts) under the management of four different landowners were involved in the test program in the northern Sacramento Valley. Table 2 summarizes the orchard and irrigation system characteristics that were involved in the evaluation of the IMO. Two farms were small family farms having 2 to 3 irrigated fields and a total of about 30 to 100 acres of orchard crops. Both of these farms relied upon pumped groundwater for irrigation. A third farm was a family incorporated farm consisting of about 20 fields having about 800 acres of orchard crops. Both surface water and groundwater were used for irrigation and they had pipeline infrastructure that allowed them to combine or interchange water sources. A fourth farm was a larger, corporate farm with about 100 orchards and total irrigated acreage exceeding 4,000 acres. Groundwater was the sole source of water for irrigation and each orchard had its own irrigation well. Pipeline infrastructure was in place in a few instances that would enable combining or interchanging water sources between a few orchards. All of these orchards are irrigated with drip or micro-sprinkler systems.

Table 2. Summary of orchards involved in the evaluation of the IMO in Tehama County, CA.

Farm ID	Orchard #	Age (yrs)	Crop & Acres	Irrigation System	Average Hourly Water Application rate & Distribution Uniformity (%)
Dairyville	1	4	Walnut – 28 ac	Minisprinkler	0.089 in/hr, 94.3%
Richfield	1	14	Prune – 28 ac	Drip	0.023 in/hr, 89.9 %
West Corning	1	14	Almond - 40 ac	Microsprinkler	0.069 in/hr, 90.0 %
West Corning	2	2 - 3	Walnut – 80 ac	Drip	0.025 in/hr, 90.6 %
West Corning	3	3 - 4	Walnut – 40 ac	Minisprinkler	0.062 in/hr, 85.0 %
West Corning	4	14	Walnut – 120 ac	Microsprinkler	0.070 in/hr, 86.7 %
Vina	1	10	Walnut – 122 ac	Minisprinkler	0.073 in/hr, 91.6 %
Vina	2	15	Walnut -113 ac	Solid set sprinkler	0.11 in/hr, 80.1 %

IMO Set Up, Field Calibration, and Routine Data Input

In April 2009, I began working with each farm cooperator to set up the on-line irrigation scheduling program (IMO) for each farm and its respective orchards. This involved inputting technical data related to each orchard. Specific types of data included soil properties, crop type and condition, and irrigation system design and performance parameters. Some variables that could potentially influence the forecasted irrigation schedules were unknown initially. They included the number of emitters per irrigation line, discharge rates from discrete emitters, effective wetted area of drip and microsprinkler systems, flow distribution uniformity, volumetric water content at field capacity, and available water holding capacity of soils. Additional field evaluation was required to define them. If a management variable could not be determined quickly in the field, rough estimates or preset default values were used initially to calibrate the IMO program and then refined as field data was collected and analyzed during the 2009 season. By the end of the 2009 season, the calibration process for orchards on each farm was completed and little adjustment was needed in 2010. A representative of each farm logged on to the website http://oiso.bioe.orst.edu/RealtimeIrrigationSchedule/index.aspx, approximately weekly during each irrigation season to input irrigation dates and irrigation set times. They also explored various features of the program and received weekly email messages that forecasted irrigation frequency and set times for the upcoming 14 day period.

Data Collection to Validate IMO Weekly Irrigation Scheduling Forecasts and Recommendations

During the course of the two irrigation seasons, a field assistant and I performed irrigation system evaluations in these orchards to determine representative water application rates and flow distribution uniformity; monitored applied water weekly in these orchards using flow meters; monitored weekly soil moisture conditions in the crop root zone to a depth of six feet with a neutron soil moisture probe; and measured weekly levels of crop water stress using midday stem water potential and a pressure chamber. The volumetric soil moisture data was inputted into the IMO to validate, and if necessary adjust, the soil moisture conditions that were forecasted by the IMO. Monitoring of applied water, soil moisture, and crop water stress was performed from April through October in 2009 and from March through October during the 2010. Time was allotted weekly for data input, analysis, interpretation, and follow up with the cooperating growers.

Cooperator Interactions and Interviews to Assess Adoption of IMO

I interacted weekly with each grower cooperator during both irrigation seasons to support the grower cooperators in all phases of learning about the IMO and using it. This included IMO program set up and calibration, routine input of irrigation operational data, field validation with soil moisture measurements, receiving and understanding weekly delivery of a 14-day forecasted irrigation schedule, and accessing and interpreting other more in-depth results given in the advanced plots section of the IMO. I also provided each grower cooperator with a weekly summary of the field monitoring results in Excel format as email attachments. These summaries included a simple water budget comparing cumulative applied water and in-season rainfall to cumulative ETc, volumetric soil moisture levels in one-foot increments to a depth of six feet to assess how much soil-water storage was contributing to the crop's water needs, and status of orchard water stress indicated by midday stem water potential. The Excel summaries were designed as a quickly accessible, backup and augmentation to the results given in the Advanced Plots section of the IMO program.

Charles Hillyer, of Oregon State University and principal technical support provider for the IMO and I met in person with each of the farm cooperators in August 2009. We had completed much of the farm set up and field calibration within the IMO for each farm and the respective orchards. Only refinement of the field calibration remained. Each grower had approximately 5 months of experience with inputting irrigation operational data into the IMO program prior to the meeting and interview. Charles provided an overview of the IMO program and was able to interview each cooperator concerning their experience with inputting data into the IMO program. I was able to interject experience and insight about providing technical support during the farm set up and field calibration process and validation of the IMO's irrigation scheduling recommendations. Each meeting and interview lasted between 2 to 3 hours. It allowed an assessment of each grower's experience with using the IMO; technical support needs for each grower to set up the IMO program for their farm and calibrate it for their specific setting; identify

real or potential benefits of the IMO program in making on-farm irrigation management decisions, and constraints to grower adoption.
Crop Coefficient Validations and Updates

Prior to beginning this IMO project (2008), we began collecting ET data over the almond orchard at the West Corning farm in Tehama County. During 2009 and 2010, actual crop evapotranspiration (ETa) was measured in the West Corning almond orchard using energy balance methods. Measurement of ETa in this orchard helped confirm whether the crop coefficients (Kc) used in the IMO program were appropriate. In August 2010, energy balance stations were installed in the walnut orchard located in Dairyville to measure in-situ ETa. Data collection will continue in 2011 and be expanded to include orchard #3 at the West Corning farm and prunes with the Vina cooperator.

<u>*Results*</u>

Grower Use of the IMO

- All four growers repeatedly logged into the IMO website during the 2009 and 2010 seasons and used the program to some extent.
- None of the four cooperators were able to initiate the setup and calibration of the IMO program without support.
- Each cooperator became proficient at inputting irrigation dates and set times into the program on a weekly or biweekly frequency. None of the growers inputted volumetric soil moisture content. My field assistant or myself inputted the soil moisture data.
- Some of the growers explored the different types of outputs provided by the IMO. All of the growers received weekly emails of the 14 day forecasted irrigation schedules for their respective fields in 2010. Due to their initial unfamiliarity with the IMO, they postponed receiving the email forecasts until the first year of the project was completed.
- Only one of the four cooperators routinely inputted irrigation dates and set times on a weekly basis from the beginning through the end of the irrigation season, which allowed this small farm operator to consider using the IMO recommendations on a real-time basis. The larger farms with more orchards per water management unit and busier day-to-day schedules tended to fall behind on their data input so the IMO 14 day forecasted irrigation schedules were not always based upon up-to-date irrigation records and as a result were sometimes erroneous. The larger farm cooperators fell behind in data inputting particularly during the harvest season from approximately mid August through the month of September. Their time and focus was on harvest and other aspects of farm management. They did catch up after the harvest season ended and the IMO output provided records to study in retrospect and to pose management changes for the next year.
- All four cooperators contacted me repeatedly concerning failed access to the IMO website.

Highlights of Grower Opinions and Feedback on IMO

Strengths:
- IMO is comprehensive and based on sound science and concepts.
- IMO is holistic and seeks to capture the many facets (crop, soil, water and energy costs, economics, salinity, etc…) that affect irrigation management decisions.

- It is an effective teaching tool for growers to expand their technical knowledge of irrigation management.
- Archived data and results were viewed as valuable for keeping irrigation records and learning from previous experiences. The records could be particularly valuable to teach, prepare, and pass on management responsibilities to the next generation of farm managers.
- The goal of providing real-time advice and communication of irrigation needs is appropriate and desirable.
- The goal and intentions of the “Water Use Plot” in the IMO output is on the right track. One of the cooperators confirmed that they expect water years where water supplies will be limited to the extent that management tools will be needed to assist them with developing a rationale for how to prioritize where to apply the water to receive the largest return. Such a tool could also guide their decisions in determining how much land to develop into perennial orchard crops.

Weaknesses:

- Concern over the fate of data inputted into a public, on-line database will discourage grower use regardless of assurances of privacy and security. Uses of water resources are competitive and controversial among urban, environmental, and agricultural interests. Growers perceive a risk of their critics using such a database negatively.
- The comprehensive nature of IMO is a “two-edged sword”. While geared to be scientifically sound and holistic, it is too complicated for growers to utilize without a significant amount of technical support. Few farms will have the technical expertise in-house to use the IMO independently. One grower viewed the program as “having too many bells and whistles” and well beyond his need. This same farmer opined that a program similar to “Water Right” developed by CSU-Fresno Center for Irrigation Technology would suffice if it had the capability to save the water management units and archive data that had been inputted previously.
- The web-base interface and line-by-line inputting of irrigation data was generally viewed as cumbersome and too slow and access to the website was at times unreliable.
- The IMO program would benefit from the development of a “Help” feature to assist the user with navigating through the program and interpreting the program outputs.
- The larger farm cooperators, Vina and West Corning, are currently using a variety of remote sensing devices, radio telemetry, and even bar coding technology to acquire real-time soil moisture or soil tension data, groundwater level data, on-site precipitation, flow meter data, and various types of inventory data. Plus, the Vina farm cooperator who used to operate a neutron soil moisture probe several years ago views the instrument as obsolete due to regulatory constraints and other available options. While the ability to input volumetric soil moisture data and verify the predicted soil moisture levels within the IMO is a desirable feature, the limitation on the type of soil moisture sensing device and the requirement to input the data manually renders the feature impractical. While the IMO is on the cutting edge in terms of scientific concepts, it is lagging behind the private irrigation and agricultural industry in terms of automation, the types of sensory technology it can accommodate, and in the methods of delivering real-time information (i.e. email is no longer state of the art).
- Three of the four farm cooperators currently use a pressure chamber to measure levels of orchard water stress to help guide their irrigation decisions. The Vina farm suggested adding a feature that enables midday stem water potential data to be included in the IMO. It would add confidence to the IMO’s irrigation scheduling forecasts. Other types

of plant-based indicators are likely to become available in the future so further development of the IMO should include the capacity to incorporate plant-based indicators of crop irrigation needs.

PI Summary Remarks and Recommendations

The current status of the IMO reflects an admirable and diligent effort by Oregon State University engineers over several years and support by the NRCS and other entities. It was a privilege to have an opportunity to become familiar with the program and evaluate its use in California nut and fruit orchards irrigated with microsprinkler and drip irrigation. Furthermore, it is acknowledged that development of the IMO is a work in progress and future opportunities to contribute to its development would be welcomed. Some general closing comments and suggestions are highlighted below in regards to the future development of the IMO:

- The IMO currently appears to better suit annual crops or alfalfa where full coverage irrigation systems such as flood, furrow, or impact sprinkler are used and questions about effective root zone are more easily modeled. The IMO needs more development and evaluation before it is be employed broadly by nut and fruit crop growers.
- Technical aspects related to effective wetted area, crop root zone assumptions, and accurate measurement of applied water were observed to sometimes result in inappropriate irrigation scheduling forecasts. Building the capacity to incorporate applied water measured with flow meters instead of computing it based upon site specific irrigation system design features and including plant-based field measurements to complement predicted and measured soil moisture levels would give added confidence to the 14 day forecasts. Also, past irrigation experiments in orchard crops such as almond and walnut may provide opportunity to evaluate production functions for orchard crops and assist with building the economic component of the IMO for orchard crops.
- The current web interface, program setup, and calibration process does not favor grower adoption. Guidance on how to navigate the program is largely absent, line-by-line data input is not efficient, and program setup and calibration requires considerable technical expertise that most growers are unlikely to have on their own. The latter point raises the question about who is available to provide technical support to gain adoption of the IMO, especially if it's features continue to change as it is developed. Entities that are positioned to provide technical support may represent the first level of users to engage rather than growers. This might include water districts, resource conservation districts, or consultants in the private sector.
- The IMO offers a comprehensive, science-based program conceptually but some of the technological aspects of acquiring the data and delivering irrigation forecasts lags behind technology currently offered by the private irrigation and agricultural industry. This raises the question whether developers of this public program should try to engage the private sector to more successfully incorporate state of the art data acquisition and information delivery systems.

Updated Almond Crop Coefficients (Kc)

Results from measuring actual crop evapotranspiration (ETa) with energy balance methods for the almond orchard on the Corning West farm for three seasons (2008-2010) are shown in Figures 1-3. The observed Ka values were considerably higher than those reported in the literature. During mid-season, the Ka values were on the order of 1.00 to 1.20 with slightly higher values in 2010. We are still investigating the reason for year-to-year variability.

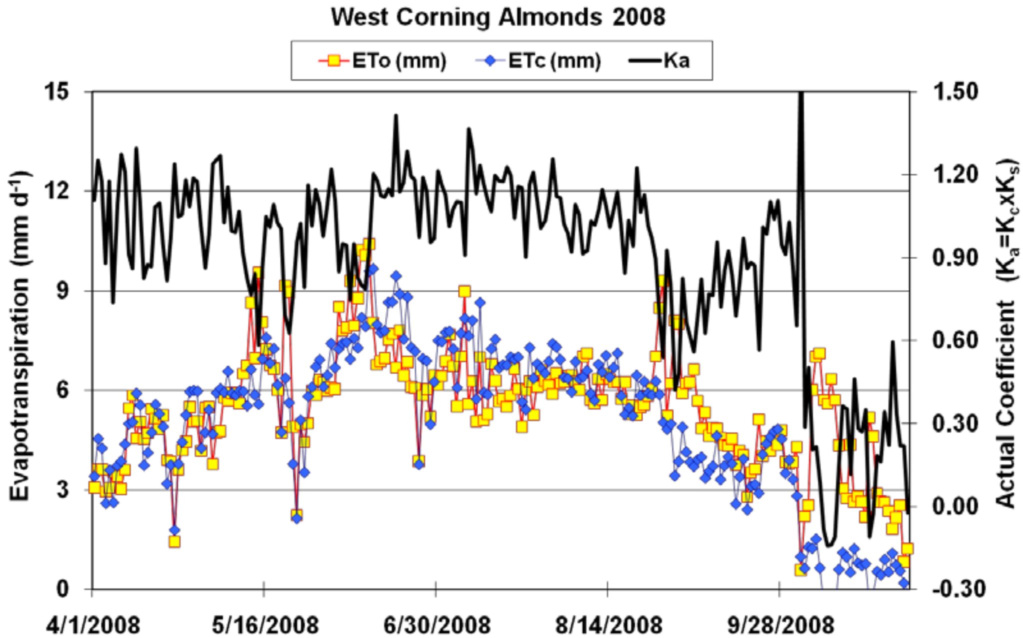


Figure 1. ET and $K_a = K_c \times K_s$ data from West Corning in the Sacramento Valley during 2008.

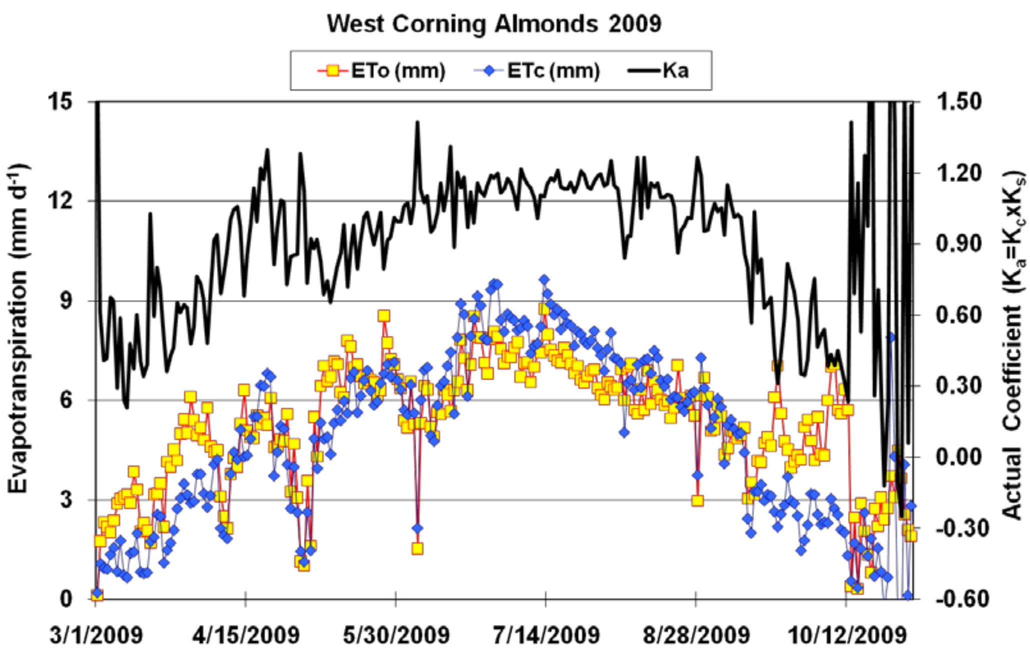


Figure 2. ET and $K_a = K_c \times K_s$ data from West Corning in the Sacramento Valley during 2009.

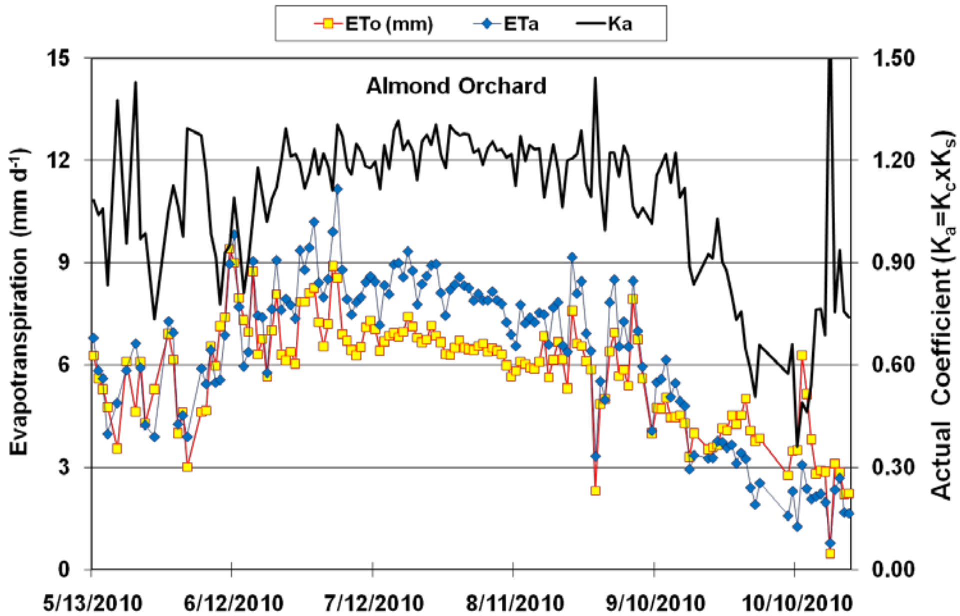


Figure 3. ET and $K_a = K_c \times K_s$ data from West Corning in the Sacramento Valley during 2010.

In 2010, evapotranspiration was also monitored at the M&T Ranch near Chico, California in cooperation with Joe Connell, Farm Advisor Butte County. The ETo, ETa, and Ka = Kc x Ks data from 2010 are plotted in Figure 4. The Ka values were slightly less but similar to the values at West Corning.

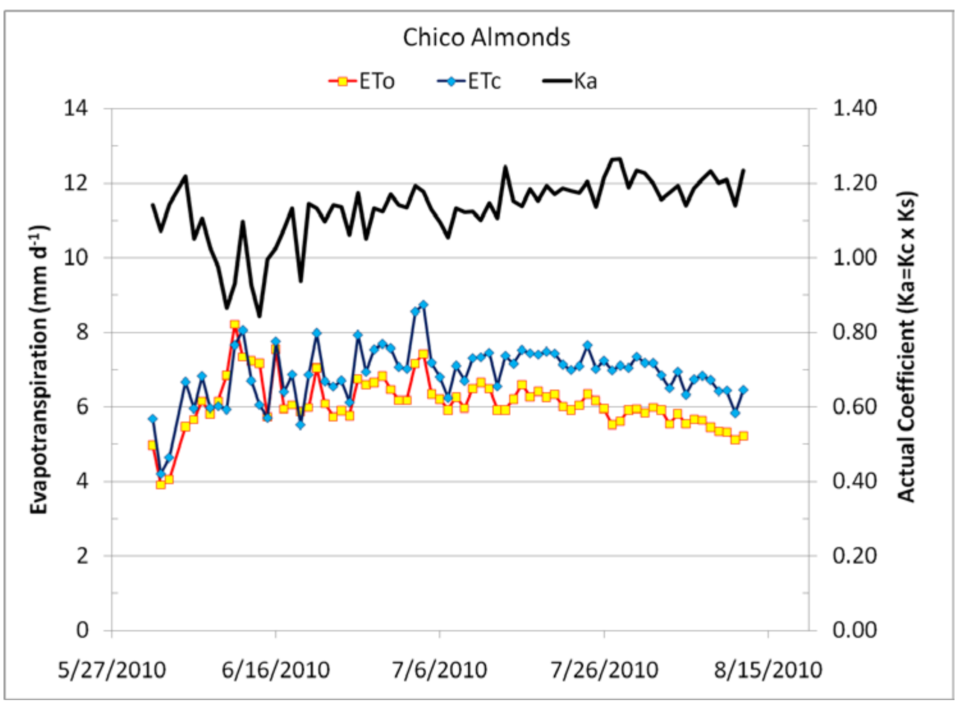


Figure 4. ET and Ka = Kc x Ks data almond orchard near Chico in the Sacramento Valley during 2010.

Results from the San Joaquin Valley (Kern County)

Prepared by: Blake Sanden, Irrigation & Agronomy Advisor

Project Demonstration Setting

More than 40 hours of outreach occurred during March and April 2009 to secure and provide preliminary training to five grower cooperators farming almonds and pistachios using micro-sprinkler (fanjet) or drip irrigation systems. From May 1-13, 2009 a total of 34 monitoring sites were installed consisting of a PVC neutron probe access tube to a depth of 9 feet and a small in-line flow-meter fitted to the hose/emitters serving that site. Four monitoring sites with access tubes to a depth of 6 feet were in existence from earlier studies to provide a total of 38 monitoring sites over 22 fields, each of which has been monitored weekly since the middle of May 2009. Many measurement locations (i.e. 28) were chosen at each site because either Watermark blocks (electrical resistance sensors) or tensiometers were already installed at the site.

Eight second count readings of neutron backscatter at one foot increments with a Campbell Pacific Nuclear Hydroprobe 503 DR (neutron probe) provide a measurement of soil water content with depth every week. These readings, combined with the metered record of applied water for the week, are supplied to the growers via email every Wednesday or Thursday so that they can update field soil moistures and irrigations in the IMO program on a regular basis.

Grower Adoption

Considerable effort was expended to encourage use of the IMO software by cooperating growers. Unfortunately, the growers did not feel comfortable with the original IMO format and complexity of content due to 1) lack of time spent to become completely familiar with the entry protocols and 2) having found their initial entry sessions to be somewhat cumbersome and that weekly data entry has to be done on a line by line, depth by depth basis for each field instead of allowing a sort of “one-stop” Excel file type upload. As a consequence, the growers tended to look at the processed/averaged neutron probe soil water content data and a summarized “percentage available moisture” that was provide with our weekly monitoring, They continued with their “normal year” scheduling as long as the field was not to dry or too wet. (See Table 1 for an example.)

An additional 20 hours of consultation over the 2010 season with the five cooperating growers did little to alter their initial opinions about the IMO program from the 2009 season. This problem is compounded by the fact that at the start of this irrigation season we told them that a simpler, more user friendly version of the IMO program would be available late spring and, at that time, we would do more training to facilitate their irrigation scheduling operations. Unfortunately, due to programming difficulty, the project was unable to deliver a simpler program and growers pretty much maintained the status quo from 2009 (i.e. they just reviewed our “soil moisture update” email and, if needed, adjusted their irrigation scheduling by hand calculation.

Our technical staff has continued to enter all current soil moisture data in an attempt to encourage program access and use by the cooperators, but we have not been actively contacting them to encourage them to log on due to the above reasons

Table 2. Example of compiled weekly soil moisture report sent to each grower cooperator containing the fields for that grower, soil water content at the indicated date and applied water to each field at the monitoring site location over the previous week.

	Soil Water Content (in/ft)					9/27/10		ETo (in)	1.24	Rain (in)	0.00	AVAILABLE WATER			
	PLOT #	DEPTH								TOTAL		Rootzone to 5'		Irrig	Cum
	Check	1	2	3	4	5	6	7	8	9	0-5FT	6-9FT	%	Inch	(in)	(in)
602 Alm NE	NP	1.00	0.70	0.80	1.49	1.66	2.79	1.90	1.83	0.97	5.64	7.49	9%	0.64	**2.38**	59.41
605 Alm SE	NP	1.52	1.49	1.07	0.73	0.56	0.52	0.59	0.49	0.52	5.37	2.13	5%	0.37	**0.81**	47.83
602-605 Avg	***9/27***	1.26	1.17	1.00	1.13	1.23	1.89	**18"**	**36"**		5.79	6.99	11%	0.79	1.31	52.15
							tension (cb)	0	-75							
606E Alm SW	NP	1.21	0.90	1.28	1.93	1.97	1.69	2.52	1.90	1.14	7.29	7.25	33%	2.29	**0.02**	38.34
606W Alm NE	NP	1.59	1.25	0.97	1.28	1.21	1.21	1.76	1.11	2.11	6.30	6.19	22%	1.30	**0.15**	30.57
606 Alm	***9/27***	1.40	1.07	1.13	1.61	1.59	1.45	**18"**	**36"**		6.79	6.72	27%	1.79	**0.09**	**34.45**
							tension (cb)	-37	0							
601 Alm SE	NP	1.25	1.31	1.14	1.18	1.49	2.35	2.62	3.03	3.34	6.36	11.35	19%	1.36	**0.75**	49.22
307 Alm NW	NP	1.83	1.52	1.90	1.56	0.87	0.73	0.56	0.49	0.42	7.67	2.20	38%	2.67	**1.28**	44.68
601-307 Avg	***9/27***	1.54	1.42	1.52	1.37	1.18	1.54	**18"**	**36"**		7.02	6.77	29%	2.02	**1.01**	**46.95**
							tension (cb)	0	-39							
601B Pist E	Pist	1.20	1.31	1.80	2.90	4.39	4.70	4.58	4.33	4.39	11.61	18.01	41%	4.11	**0.29**	18.65
601B Pist W	Pist	1.10	1.17	1.20	1.04	2.56	3.53	0.00	0.00	0.00	7.06	3.53	7%	0.56	**0.32**	20.58
601B Pist	***9/27***	1.15	1.24	1.50	1.97	3.48	4.12	**18"**	**36"**		9.33	10.77	24%	2.33	**0.30**	**19.62**
							tension (cb)	-58	-24							
Cherries	***9/27***	1.46	1.09	1.22	2.79	2.48	1.19	1.26	1.73	1.63	9.03	5.81	58%	4.03	**0.78**	38.83

Evaporanspiration and Crop Coefficient Development

Actual crop evapotranspiration (ETa) was measured over an almond orchard at Paramount Farming during 2008, 2009, and 2010. The product actual coefficient Ka = Kc × Ks was determined as the ratio ETa/ETo with ETo coming from the nearby CIMIS station. The ETo, ETa, and Ka data from the energy balance surface renewal (EBSR) measurements for 2008 are shown in Figure 5. The results from the energy balance sonic anemometer (EBSA) measurements are shown in Figure 6. The Ka results were similar for the two methods except for a bit more fluctuations in the EBSA data.

Mean weekly Ka = Kc × Ks values for the three seasons are plotted in Figure 7. A plot of the weekly mean Ka values, averaged over 2008-2010, Kc values used in Kern County during recent years, and Kc values widely used in the San Joaquin Valley from older literature is shown in Figure 8. Clearly, the new coefficients are higher than those used in Kern County and they are considerably higher than the older San Joaquin Valley coefficients. Although reasons for the higher Ka values are not definitive at this time, the higher values are likely due to more dense plantings, frequent micro-sprinkler irrigation, and better management than 30-50 years ago. Also, the measurement methods used today are likely to be more accurate. Coefficient data from the Sacramento Valley and from Fresno County were similarly higher than in the past. Note that there was a dip in the Ka during late-August and early-September that was likely due to a cutback in irrigation during harvest. The large dip in Kc during October and November 2010 (Fig. 7) was likely due to rainy weather and instrument problems. Of course that affected the November dip during November (Fig. 8).

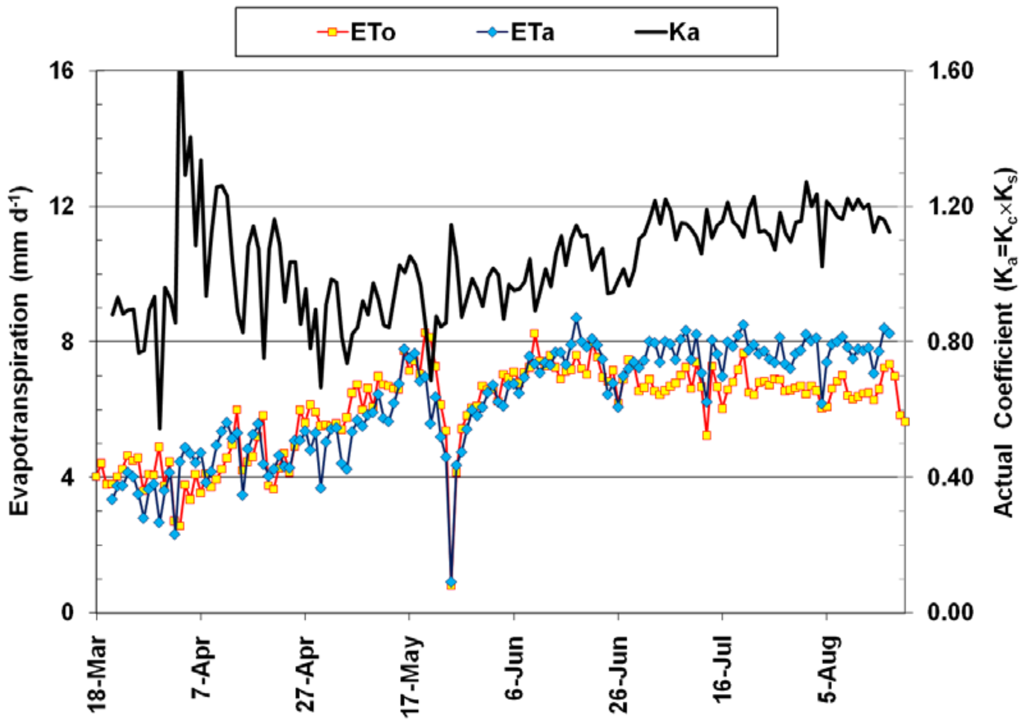


Figure 5. Reference (ETo) and actual (ETa) crop evapotranspiration rates from the EBSR method collected during 2008 in Kern County.

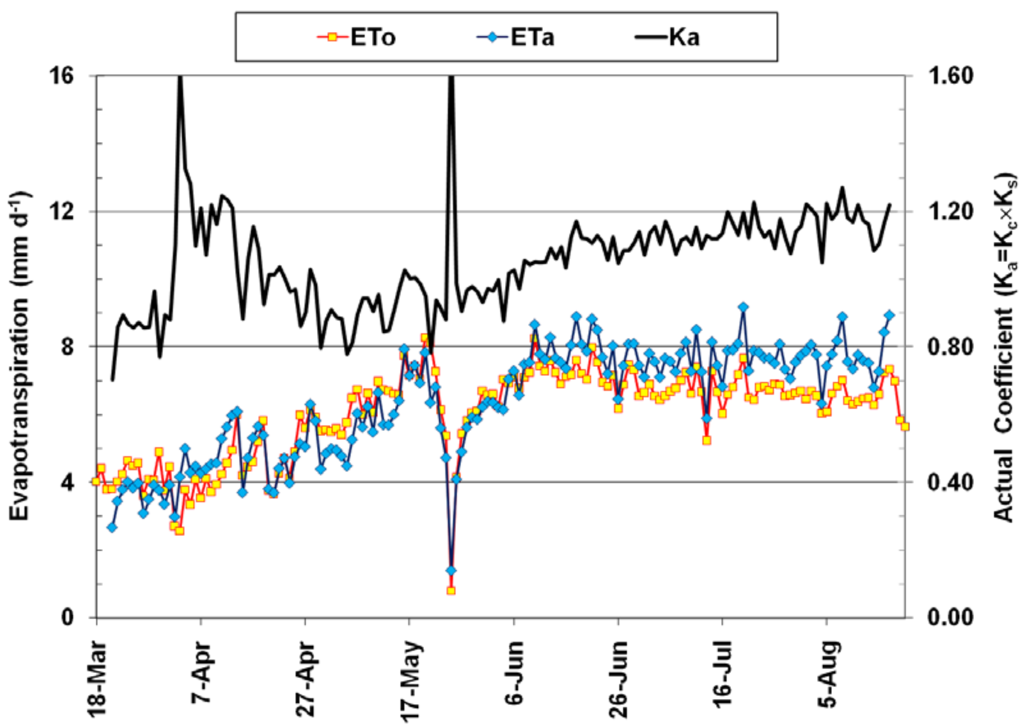


Figure 6. Reference (ETo) and actual (ETa) crop evapotranspiration rates from the EBSA method collected during 2008 in Kern County.

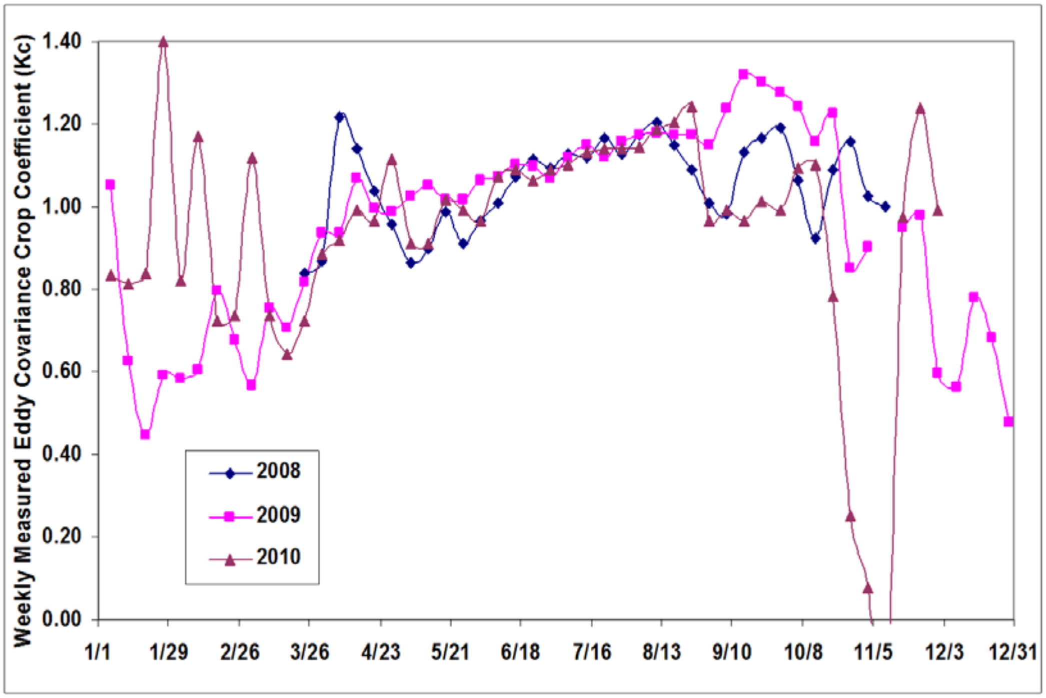


Figure 7. Mean weekly actual coefficient Ka = Kc × Ks values for almonds during 2008, 2009, and 2010 seasons

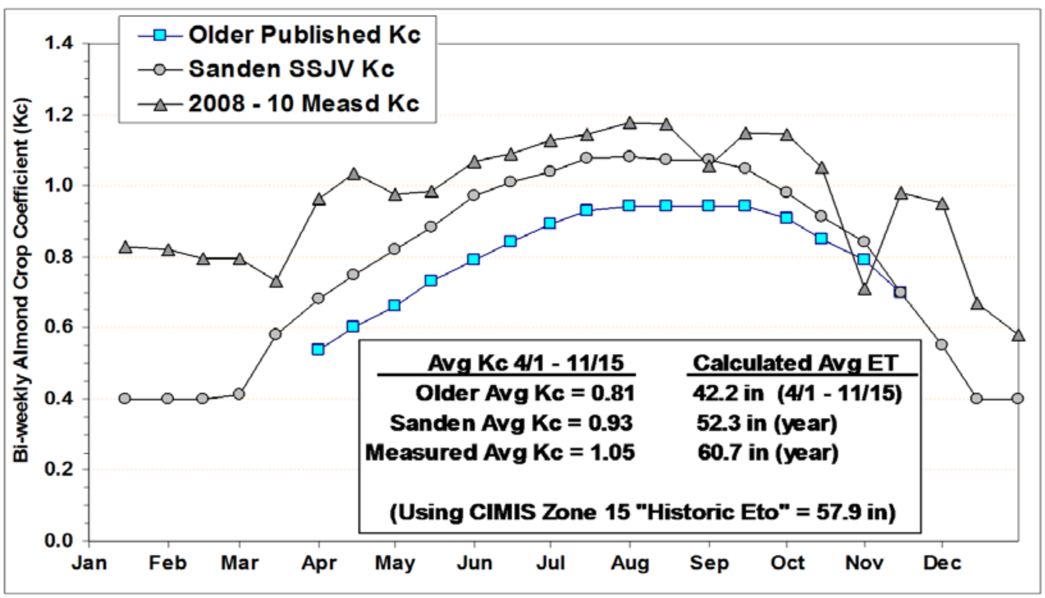


Figure 8. Mean bi-weekly actual coefficients Ka = Kc × Ks for almonds averaged over 2008-2010, Kc values used in Kern County during recent years, and older published Kc values for the San Joaquin Valley (Fereres and Puech, 1982). Note that the Ks = 1.0 was assumed for the Ka = Kc × Ks data prior to this project.

The following activities served as vehicles to discuss and promote scientific irrigation scheduling in general and the IMO program in particular where appropriate.

1. More than **40 hours of outreach** was used in March and April, 2009 to secure and provide preliminary training to **5 grower cooperators farming almonds and pistachios** using microsprinkler (fanjet) or drip irrigation systems.
2. One Kern County irrigation workshop on April 8, 2010 with a newsletter and meeting handout (attached). 54 attending.
3. One statewide popular press interview and article: "Farmers look at net returns when making irrigation plans". Ag Alert Apr 26, 2010 pp.7-8
4. One statewide irrigation symposium with a session on irrigation scheduling 2/2/10, flyer attached. 88 attending.
5. Six grower irrigation scheduling consultations on farms and in office

Report from the San Joaquin Valley (Fresno County)

Prepared by: Daniel Munk, Irrigation & Agronomy Advisor

We completed our initial goals and objectives aimed at developing new information on the water use and irrigation management habits of San Joaquin Valley Almond growers by observing field management practices and monitoring specific water management parameters. Our local team has continued to monitor one grower site near Firebaugh, CA and is continuing its efforts to build an appropriate data base for testing the IMO scheduling program initiated by the Department of Engineering and Bio-Resources at Oregon State University. Our goal is to develop a data base that can test a variety of farm water management variables and work to increase the farm water decision options thereby improving farm water efficiency and manage problems caused by improper irrigation management. We believe that knowledge gained by developing detailed information on a small number of fields will later translate into a more broad understanding of farm water management problems and assist in finding solutions.

The orchard we monitored was a high yielding almond orchard using a water management regime similar to other fields operated by the grower as well as other farms in the region. The monitoring field utilizes double row drip, as does the majority of Almonds fields in this region and is scheduled with the assistance of the CIMIS (California Irrigation Management System) weather system and verified by the data we are collecting using the surface renewal (SR) and eddie covariance (EC) methods that were installed in the winter of 2008. The cooperating grower also developed similar strategies using the IMO program for evaluating whole farm water supply management and incorporated learning from the study field to establish weekly water applications to other almond orchards on the farm.

Together with the support of a field technician, we were able to accomplish the major goals and objectives that we established for the project. This year's monitoring activity included developing soil water information using the neutron probe to establish multiple location soil water readings, midday stem water potential readings and together with Department of Water resources maintained and developed the SR and EC stations and data. Eight neutron probe tubes were monitored on a 7 to 9 day interval along with stem water potential readings on multiple trees. We summarized the water applied and soil water extraction information. At each visit we maintained the SR and EC equipment and downloaded the necessary data for the ETa calculations. The seasonal ET and Ka plots from 2009 are shown in Figure 9.

In terms of outreach activities, I participated in a March 2, 2010 regional meeting by presenting project goals and objectives as well as summary findings to more than 50 almond and cotton growers. This meeting was sponsored by UCCE and organized by the San Joaquin

Sustainable farming project in Dos Palos. I also participated in a UCCE/Sustainable Farming Systems field day held near Los Banos on June 23, 2010 to discuss some of the findings from this farm water management program to more than fifty growers and industry participants.

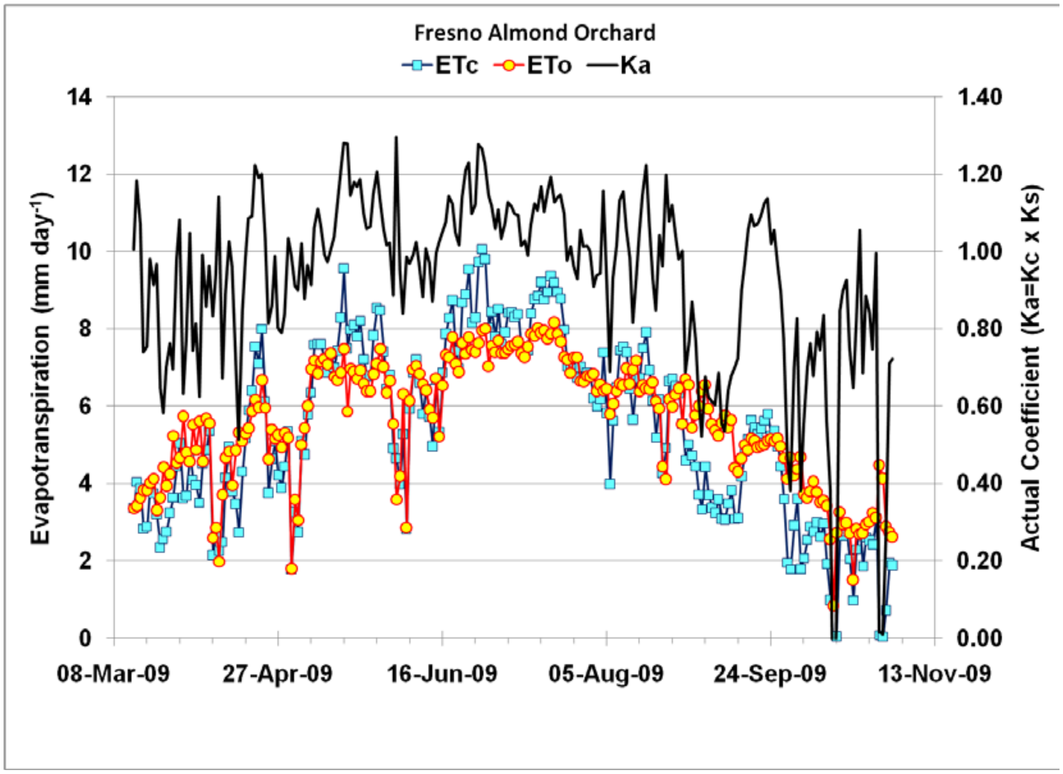


Figure 9. ET and Ka = Kc x Ks data from the Fresno County almond orchard in the San Joaquin Valley during 2009.

Report on the Oregon State Scheduling (IMO) Model Development

Prepared by Marshall English, Professor of Biological and Agricultural Engineering

Systems analyst/programmer support

The Oregon State research team has worked with the system analyst to: (i) redesign of the IMO system, and (ii) providing training in use of the IMO system. The primary focus for this year has been evaluation and support of the features developed last year. Technical support was provided (and continues) to the farm advisors and some growers during the 2010 irrigation season. Particular attention was given to calibration of the participating farms using data from the previous year. Numerous bug fixes where implemented prior to and during the two-year project. Some interface enhancements where developed to facilitate spread sheet upload of soil moisture measurement data. Also, requisite system maintenance for the server, database, and software systems was performed.

Development and implementation of the Bayesian method for utilization of soil moisture measurements continued during this year. We developed the theoretical framework necessary to integrate the Bayesian method with the Irrigation Efficiency Model's internal representation of soil moisture. Preliminary implementation of this framework has begun.

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Velocity Contour Weighting Method for Increased Accuracy of Upward Looking ADVM in Irrigation Channels

Basic Information

Title:	Velocity Contour Weighting Method for Increased Accuracy of Upward Looking ADVM in Irrigation Channels
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Publications

1. Howes and Sanders (2011a) Howes DJ and BF Sanders (in press) Velocity Contour Weighting Method I: Algorithm Development and Laboratory Testing. ASCE Journal of Hydraulic Engineering, doi:10.1061/(ASCE)HY.1943-7900.0000451.
2. Howes and Sanders (2011b) Howes DJ and BF Sanders (in press) Velocity Contour Weighting Method II: Evaluation in Trapezoidal Channels and Roughness Sensitivity. ASCE Journal of Hydraulic Engineering, doi:10.1061/(ASCE)HY.1943-7900.0000452
3. Howes (2010). Howes, Daniel J, 2010, Improving acoustic Doppler velocity meter accuracy for open channel discharge measurement, Ph.D. Dissertation, Department of Civil and Environmental Engineering, University of California, Irvine, California, 162p.

Problem and Research Objectives

Acoustic Doppler Velocity Meters (ADVM) provide an alternative to traditional open channel flow measurement techniques such as stage-rating, flumes, and weirs. Installations of flumes and weirs require a significant capital investment and sufficient head (10-15% of total depth) (Replogle 1997). Head differences across the structure make the flow rating insensitive to downstream conditions and enable critical flow, two factors that support a high degree of accuracy (Chow 1959; Replogle 1997). Unfortunately, the necessary head is not always available, transitions to supercritical flow can create erosion problems, many designs trap sediment, and flumes can be difficult to configure for a wide range of flow rates and water levels (Replogle and Kruse 2007).

Pulsed ADVMs utilize acoustic transducers which transmit an acoustic beam as a pulse of a known frequency along a narrow path (Morlock et al. 2002; Styles et al. 2006). When the pulse hits sediment or air bubbles suspended in water, it scatters and some of the sound signal returns back to the transducer. The time it takes for this "return signal" or backscatter to return to the transducer depends on the distance along the beam path at which the sediment or air bubble is located. Factors affecting the resolution of the velocity measurements include ADVM operating frequency, pulse length, fixed pulse repetition frequency, and properties of the water that affect the speed of sound such as temperature and salinity (Hardcastle and Thorne 1997). The frequency of each backscatter signal has a Doppler shift that is proportional to the fluid velocity (Morlock et al. 2002). The set of return signals therefore provides a set of distances and velocities at that moment, measured within the limited sample area of the acoustic beam.

ADVM installations in channels may utilize either side-looking configurations that sample horizontally through the cross section, or upward-looking (bottom-mounted) configurations that sample vertically through the cross section. Because of its improved accuracy in channels with variable flow depths (Styles et al. 2006), this study focuses on a pulsed, upward-looking ADVM that is mounted at the centerline of the channel and uses two velocity measurement beams.

Device software requires that information on channel geometry be input manually for the ADVM sensor to estimate discharge. Velocities are only measured by the ADVM within a small volume of the flow cross section. Therefore, in a typical cross section, an ADVM does not provide an cross-sectional average velocity, but rather a sample of the velocity distribution in a vertical plane aligned with the channel centerline. Assumptions regarding the relationship between the ADVM sample velocity and the cross-sectional average velocity are typically provided within the manufacturer's software. One example is the approach presented by Huhta and Ward (2003) where a depth integrated power-law equation was used to relate the average ADVM sample velocity to the cross-sectional average velocity (V). However, this method has performed poorly in field applications (Styles et al. 2006).

Howes et al. (2010) describe a subcritical channel contraction design that can be used to achieve a high degree of accuracy with an upward-looking ADVM. The contraction causes rapidly varied flow that creates a relatively uniform cross-sectional velocity distribution near the contraction entrance. This makes the ADVM sample velocity a good proxy for the actual cross-sectional velocity for Froude numbers up to 0.5. Without calibration, the cross-sectional velocity can be measured within +/-4% for Froude numbers below 0.5.

While the accuracies presented in Howes et al. (2010) are considered very good for open channel flow measurement, installation of an ADVM in subcritical contraction with a Froude number below 0.5 is not always feasible and can be costly given site constraints. It should be noted that any flow measurement section including the subcritical contraction should be located in a long straight section of unobstructed flow with a consistent concrete (or equivalent) lined cross section (Styles et al. 2006).

Channel flow is typically classified as prismatic Gradually Varied Flow (GVF) in most irrigation channels because of inline control structures. Hence, flow is not strictly uniform due to backwater effects. Nevertheless, ADVMs are commonly deployed under these conditions, and a calibration procedure termed the index-velocity method (also referred to as the Flow Rate Indexing Procedure (QIP)) is the most common method of converting the sample velocity into the cross-sectional average velocity. The index-velocity method has been incorporated into the software run by many ADVM devices (Patino and Ockerman 1997; Morlock et al. 2002; Styles et al. 2006). The method takes the average of the sample velocities as a proxy for the true average velocity, and calibrates the ADVM based on site specific attributes that are impacting the measured velocity in relation to the actual cross-sectional velocity. These attributes, the effects of which are lumped together, include channel geometry, water depth, velocities in the unmeasured “buffer” region, and boundary roughness. The primary disadvantage of the index-velocity method is that, in order to account for all attributes, at least 10 individual calibration points at differing flow and depth conditions are recommended (Styles et al. 2006). Hence, it is time consuming, logistically challenging, and costly to implement. Moreover, estimation of the cross-sectional average velocity stands to be improved by making use of the velocity distribution, not simply the sample average.

The objective of this project is to develop a new method for estimating the cross-sectional average velocity (and discharge), in straight prismatic GVF sections, that achieves comparable accuracies to the index-velocity without calibration. The Velocity Contour Weighting Method (VCWM) developed here, is predicated on a weighting of the ADVM velocity measurements to obtain the cross-sectional average velocity, thus the leveraging vertical distribution of velocities provided by the ADVM. The velocity weights adapt based on channel and flow properties and velocity distribution data acquired by the ADVM.

Research Methodology

The challenge to VCWM is finding the correct weighting of ADVM velocity measurements as a function of channel geometry and roughness. This is addressed by applying a validated Computational Fluid Dynamics (CFD) model to a range of channel flow scenarios that account for typical geometry and roughness properties. In each case, a repeatable surrogate of the true average velocity is obtained and it is possible to sample the ADVM velocity distribution from simulation data based on a typical instrument configuration which is selected here to be 0.034 m bin intervals in the vertical. Moreover, CFD depicts the distribution of velocity across the entire cross section so the velocity weights can be measured with a high degree of accuracy. What remains is to understand (and predict in a reliable way) how the weights depend on channel properties. Hence, dimensional analysis and empirical modeling techniques are used for this purpose. Special attention is placed on the first weight accounting for flow near the wall because the velocity is poorly sampled here and the weight is largest and most significant relative to the cross-sectional average velocity estimate.

Analysis of CFD data as described above generated an original formula for predicting the cross-sectionally averaged velocity as a non-linearly weighted average of the ADVM data, what we call the VCWM. The project continued with validation of the formula in laboratory channels and concrete-lined irrigation canals as described in Howes and Sanders (2011a) and (2011b), respectively, which appear in the *ASCE Journal of Hydraulic Engineering* as companion papers. Pre-print versions of the papers are accessible now from the journal website, and typeset versions will appear later this year. Readers interested in methodological details and results are directed to these papers. Our major findings are described below.

Principal Findings and Significance

VCWM offers several advantages over the commonly used index-velocity method. Leveraging the velocity distribution measured by the upward-looking ADVM, the VCWM algorithm breaks out the independent components of channel geometry, water depths, and surface roughness to circumvent the need for the intensive index-velocity calibration process under varying channel conditions. Channel geometry can be measured by surveying the site, water depth by the ADVM, and surface roughness can be estimated using tables in most hydraulics textbooks.

Laboratory testing shows that the VCWM can be used to estimate discharge with uncertainty less than +/-5% without calibration. This is an improvement on the +/-6% uncertainty using the conventional index-velocity method in a uniform cross section with a recommended 10 calibration points (Styles et al. 2006). The best strategy to minimize this error is to limit the buffer distance near the channel boundary provided that the ADVM interference on the velocity distribution can be minimized.

Field testing in concrete-lined trapezoidal channels shows that VCWM can be used to estimate the cross-sectional average velocity with errors of less than +/-6.3% without calibration. The tests were conducted on 51 cross-sectional velocity distributions under different flow rates, water depths, and channel geometries. The VCWM error is comparable to the +/-6% error using the conventional velocity-index rating method with a recommended 10 calibration points (Styles et al. 2006). For the sake of comparison, the most accurate technology for field installations is the long-throated ramp flume which can obtain discharge measurements within +/-2% if installed and designed properly (Clemmens et al. 1990). However, traditional flumes including the long-throated flume, can be cost prohibitive and require significant headloss which is not always available.

Sensitivity analysis was performed to evaluate potential uncertainties in the method arising from an uncertain roughness parameter. Changes in discharge of +/- 1% resulted from a range of reasonable roughness values selected for the channel boundary material. This demonstrates the insensitivity of the VCWM to the surface roughness assuming the roughness does not change significantly on a seasonal basis. In order to minimize seasonal and annual changes in surface roughness due to aquatic weed growth and sedimentation which can occur in lined channels, three to four channels widths upstream and two channel widths downstream of the ADVM should be cleaned regularly (depending on the amount of sedimentation this may be on a monthly basis).

The concrete-lined channels in this evaluation were relatively small with bottom widths from approximately 0.3 m to 1 m and side slopes from 0.87 to 1. Since the VCWM was developed using CFD simulations in relatively small channels (presented in the companion paper) and has been tested in similar situations, there is uncertainty related to how the method will perform under different channel conditions. VCWM testing in larger channels, channels with different boundary material, and channels with more significant side slopes is warranted.

The utility of this method is not necessarily limited to lined channel sections. However, with any flow measurement technique, the dynamic boundary conditions in earthen and natural channel conditions pose significant issues. These issues include sedimentation, erosion, and aquatic weed growth. Even if a method can compute the average cross sectional velocity accurately, there can be significant uncertainty in discharge computed using the velocity-area method, related to the area computation.

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Information Transfer Program Introduction

Transfer of research information to users, agencies, and policy-makers is essential for improving water quality and quantity in the state. Multiple methods are employed to ensure that land managers and decision makers have the best science available to support their activities. UC ANR coordinates and/or delivers field days, demonstrations, workshops, and classes. UC is focused on the delivery of water quality education in culturally and linguistically appropriate manners. There are policy outreach efforts to inform legislators and the public on salient water issues. UC ANR is continually developing newsletters, manuals, websites, and other publications for information dissemination and transfer

USGS Summer Intern Program

None.

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	6	9	0	7	22
Masters	4	11	0	10	25
Ph.D.	7	6	0	5	18
Post-Doc.	5	4	0	1	10
Total	22	30	0	23	75

Notable Awards and Achievements

ANR s leadership is prevalent in targeting the state s most difficult challenges, such as those addressed in the following two studies:

1. UC Researchers, in cooperation with CALFED and the State Water Resources Control Board, examined the runoff from eight neighborhoods in Sacramento and Orange counties. Water runoff samples were collected regularly during the irrigation season and during the first rains of each storm season. The samples were analyzed for 11 pesticides, fertilizers, other pollutants and pathogens. In both counties, UC Master Gardeners developed activities for homeowners to improve landscape management practices related to water, fertilizer, and pesticide use. The aim was to reduce or eliminate pollution runoff. Runoff flow in both counties showed consistent water waste from normal landscape irrigation. In Northern California, irrigation runoff was nearly five times higher than storm runoff, indicating poor outdoor water management in the dry season. In general, pesticides and pathogen indicators were found in all samples. This data helped water agencies develop customer programs on managing landscapes. Master Gardener outreach improved the landscape practices of homeowners. The flow data is also being used by a team of UC researchers to develop a model for urban planners and developers to reduce water runoff and runoff pollutants in new and existing urban landscapes.

2. ANR academics seek solutions to address water-related issues in California by collaborating with partners such as the Public Policy Institute of California. This collaboration resulted in recent studies to review alternative solutions to problems facing the Sacramento and San Joaquin Delta. This study revealed that a single episode of delta failure could reach $40 billion and would cause severe disruptions to California's water supply.

Key findings and recommendations included the following:

Although changes will result in significant costs and dislocations, most users of the Delta can adapt economically.

Any equitable solution must fairly consider losses and displacements.

Strong political and institutional leadership is needed to address the Delta crisis.

Since 2006, CALFED, the Delta's joint federal and state program, has been operating without independent authority or budget. Scientific work in the Delta needs to be refocused; as levee replacement, experiments in adapting ecosystems, flood control, and island land management should be key components of a new problem-solving framework.

As a result of this study, California's former Governor Schwarzenegger signed five landmark bills that were approved by the State Legislature to move California into a new era of water reliability that will benefit the state's residents and economy for generations to come.

3. Award 2007CA195G:

We are in discussion with the Santa Cruz County Resource Conservation District and several stakeholder groups on setting up spin-off projects in other parts of the basin, and are completing a regional GIS analysis and preparing for percolation testing in support of this effort. Development of a new basin management plan is to begin this year, and our studies of MAR will be incorporated into that effort. Finally, we have discussed with staff of the Regional Water Quality Control Board the importance of drafting new agricultural water quality requirements so that they do not prohibit the use of MAR approaches to improve water quality, and this idea has been positively received. We have secured an additional $2000 in funding from the University of California Committee on Research in support of MAR research, and are exploring options for securing funding in support of a broader (distributed MAR) research effort.

4. Award 2010CA264B:

Findings from this work have been reported to the Department of Bioresources and Agriculture Engineering at Oregon State University who are the original developers of the IMO and to the USDA-NRCS who have been important funders of its development. Strengths and opportunities for improving the existing IMO have been identified and should help to influence the development of the next generation of irrigation scheduling programs for on-farm adoption. It is our hope that these findings will be considered by the American Society of BioResource and Agriculture Engineering who have formed a task committee for envisioning and developing the next generation of Irrigation Scheduling tools.

Findings from our evaluations of crop water use in almonds using Eddy Covariance techniques suggest that water use in almonds is higher than currently suggested in literature. This is an important finding because almond is the second largest crop in terms of water consumption in California (slightly lagging behind alfalfa). This reflects adoption of more intensive cultural practices and higher crop production.

5. Award 2010CA265B:

Dan Howes is now employed as an Assistant Professor in the Bioresource and Agricultural Engineering Department at Cal Poly San Luis Obisbo. Funding provided by the Prosser Trust allowed Dan to devote considerable time to his dissertation work which undoubtedly helped him to compete for an academic job.