2004 Water Use Efficiency Proposal - Section B Agricultural Research

Project Information Form

Applying for: ☐ Urban ☑ Agricultural

1. (Section A) **Urban or Agricultural Water Use Efficiency Implementation Project**
   - ☐ (a) implementation of Urban Best Management Practice, #_____
   - ☐ (b) implementation of Agricultural Efficient Water Management Practice, #_____
   - ☐ (c) implementation of other projects to meet California Bay-Delta Program objectives, Targeted Benefit # or Quantifiable Objective #, if applicable _____
   - ☐ (d) Specify other: _____

2. (Section B) **Urban or Agricultural Research and Development; Feasibility Studies, Pilot, or Demonstration Projects; Training, Education or Public Information; Technical Assistance**
   - ☑ (e) research and development, feasibility studies, pilot, or demonstration projects
   - ☐ (f) training, education or public information programs with statewide application
   - ☐ (g) technical assistance
   - ☐ (h) other

3. Principal applicant (Organization or affiliation): David Slaughter, Bio. & Agricultural Engineering Dept. University of California, Davis

4. Project Title: Ground-based Remote Sensing Technology for Improved Agricultural Water Use Efficiency in Furrow Irrigation Systems.

5. Person authorized to sign and submit proposal and contract:

Name, title	David Ricci, Contracts & Grants Analyst
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Telephone	(530) 752-9753
Fax.	(530) 754-6008
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6. Contact person (if different):

Name, title.	David Slaughter, Professor
Mailing address.	Bio. & Agricultural Engineering University of California, Davis Davis, CA 95616
Telephone	(530) 752-5553
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E-mail	dcslaughter@ucdavis.edu

7. Grant funds requested (dollar amount): **$462,340**

(from Table C-1, column VI)

8. Applicant funds pledged (dollar amount): None

9. Total project costs (dollar amount): **$462,340**

(from Table C-1, column IV, row n)

10. Percent of State share requested (%) 100%

(from Table C-1)

11. Percent of local share as match (%) None

(from Table C-1)

12. Is your project locally cost effective?

Locally cost effective means that the benefits to an entity (in dollar terms) of implementing a program exceed the costs of that program within the boundaries of that entity.

(If yes, provide information that the project in addition to Bay-Delta benefit meets one of the following conditions: broad transferable benefits, overcome implementation barriers, or accelerate implementation.)

- ☐ (a) yes
- ☐ (b) no

11. Is your project required by regulation, law or contract?

If no, your project is eligible.

If yes, your project may be eligible only if there will be accelerated implementation to fulfill a future requirement and is not currently required.

- ☐ (a) yes
- ☑ (b) no

Provide a description of the regulation, law or contract and an explanation of why the project is not currently required.

Automated monitoring of furrow irrigation efficiency is not currently required by law.

12. Duration of project (month/year to month/year):	3 years (12/01/05 to 11/30/08)
13. State Assembly District where the project is to be conducted:	8th Assembly District
14. State Senate District where the project is to be conducted:	5th Senate District
15. Congressional district(s) where the project is to be conducted:	California's 1st District
16. County where the project is to be conducted:	Yolo/Solano
17. Location of project (longitude and latitude)	UC Davis (long.=-121.75, lat.=38.56)
18. How many service connections in your service area (urban)?	N/A
19. How many acre-feet of water per year does your agency serve?	N/A

20. Type of applicant (select one):

- ☐ (a) City
- ☐ (b) County
- ☐ (c) City and County
- ☐ (d) Joint Powers Authority
- ☐ (e) Public Water District
- ☐ (f) Tribe
- ☐ (g) Non Profit Organization
- ☑ (h) University, College
- ☐ (i) State Agency
- ☐ (j) Federal Agency
- ☐ (k) Other
  - ☐ (i) Investor-Owned Utility
  - ☐ (ii) Incorporated Mutual Water Co.
  - ☐ (iii) Specify _____

21. Is applicant a disadvantaged community? If 'yes' include annual median household income.

(Provide supporting documentation.)

- ☐ (a) yes, _____ median household income
- ☑ (b) no

Signature Page

By signing below, the official declares the following:

The truthfulness of all representations in the proposal;

The individual signing the form has the legal authority to submit the proposal on behalf of the applicant;

There is no pending litigation that may impact the financial condition of the applicant or its ability to complete the proposed project;

The individual signing the form read and understood the conflict of interest and confidentiality section and waives any and all rights to privacy and confidentiality of the proposal on behalf of the applicant;

The applicant will comply with all terms and conditions identified in this PSP if selected for funding; and

The applicant has legal authority to enter into a contract with the State.

	David Ricci, UCD Contracts & Grants Analyst	
Signature	Name and title	Date

Ground-based Remote Sensing Technology for Improved Agricultural Water use Efficiency in Furrow Irrigation Systems.

A 2004 Water use Efficiency Proposal - Section B, Agricultural Research and Development Feasibility Study

Principal Investigators:

David Slaughter, Professor; Wesley Wallender, Professor; and Shrinivasa Upadhyaya, Professor
Biological and Agricultural Engineering, University of California, Davis

Proposal Summary:

This proposal will study the feasibility of using ground-based remote sensing techniques to monitor the application of water in furrow irrigation systems in order to provide a means of substantially reducing water lost to deep percolation and tail water losses by automatically controlling the application rate of irrigation water.

This proposal addresses the following topics found in the list of agricultural water use efficiency projects of interest in the 2004 Water Use Efficiency Proposal Solicitation Package

- Applied research projects on specific soil, water, plant issues as related to water use efficiency
- Potential benefits and costs of employing remote sensing technology to improve water use efficiency
- Potential benefits and costs of improved water use practices associated with crops, crop processing, or land management practices affecting water use efficiency (for example rice, processing tomatoes, reduced tillage, grazing lands)
- Potential benefits and costs of improved furrow irrigation
- Exploration of new technologies and water management practices to improve water use efficiency

Statement of Work, Section 1: Relevance and Importance

Furrow irrigation is the oldest and most popular method of row crop irrigation throughout the world as well as in California. Important California row crops grown in the Sacramento - San Joaguin Delta region such as processing tomatoes (one of the crops in the list of agricultural projects of interest in the proposal solicitation package) and corn are commonly irrigated with furrow irrigation methods. The popularity of furrow irrigation is due in part because it is the irrigation method requiring the least capital investment. However, it is also the method with the lowest water application efficiency. The low water application efficiency comes from the fact that there is currently no precise or automated way to change the water discharge rate at the head of the furrow during irrigation. Control of furrow irrigation is done manually in California using field labor with little or no theoretical training in irrigation principles. Further, on large California farms, farm size necessitates scheduling many irrigation events such that the water will reach the end of the furrow at night, a time when manual monitoring of irrigation progress is difficult and accidental over irrigation is more common resulting in excessive amounts of water loss at the end of the furrow as excess tail water.

The water application efficiency in furrow irrigation is suboptimal because there is no precise way to vary discharge at the furrow inlet once irrigation starts. Varying the flow rate during a furrow irrigation event, as opposed to holding it constant or letting it vary arbitrarily, can reduce water lost to excess deep percolation and runoff. Deep percolation water infiltrates and passes below the root zone and is not consumed by the plant. Because water is ponded at the upstream end of the field during the time water is spreading or advancing along the furrow, excess water may infiltrate and lead to excess deep percolation at the upstream end. To reduce nonuniformity of infiltration, a control goal is to start with a high inflow rate and spread the water across the field quickly such that the ponding time and hence infiltration is more uniform. The upper limit of the flow rate, however, is constrained to prevent overtopping (submerging the top of the planting beds between furrows) and erosion. Excess deep percolation is also caused by irrigation time in excess of that required to meet requirements at locations infiltrating the least amount of water (often this is at the downstream end of the field where the ponding time is least). Hence turning off the water at the appropriate time is also part of the optimal flow control requirement.

As mentioned above, precisely controlling the inflow rate not only reduces excess deep percolation it also reduces runoff. If the high inflow rate, used to quickly advance the water across the field, is maintained during the entire irrigation event, runoff will occur in most cases. Runoff can be reduced to near zero by decreasing the inflow rate with time from the maximum at the beginning to zero at the completion of irrigation.

Optimal control of the inflow rate with time (hydrograph) depends on infiltration information. Infiltration rate during an irrigation event generally decreases with ponding time and hence with distance along the furrow but the trend can actually reverse because soils are often highly nonuniform. Infiltration rates also change from irrigation to irrigation as cultivation and antecedent soil water change the initial conditions. Infiltration information is transmitted in the time it takes for water to advance (advance time) along the furrow. If the infiltration rate is high, advance is slow and vice versus. Hence, the time when inflow rate is programmed to decline is

delayed and the rate of decline at the end of the irrigation may be greater. Knowing the advance time along the field represents infiltration information that is used to control the inflow.

Theory predicts that the application of automatic feedback control methods to the discharge rate of water into the furrow, deep percolation and tail water losses during both the advance and soaking stages could be substantially reduced. A successful application of automatic furrow irrigation control would result in considerable improvement in furrow irrigation water application efficiency in California.

Clemmens (1992) reviewed a number of methods developed for feedback control of surface irrigation using contact-type sensors manually positioned in the furrows and found that feedback control systems did consistently better than the farm irrigators in terms of net infiltrated depth and application efficiency. Clemmens and Keats (1992) found that more precise control of irrigation is possible by combining information from field conditions with observations of water advance. Hibbs et al. (1992) developed a furrow irrigation automation system utilizing an adaptive control algorithm. The performance of the automated system when compared with furrow irrigation at a constant flowrate, produced a 74% reduction in tailwater, and 39% increase in application efficiency while decreasing cumulative infiltration by 28%. Humpherys and Fisher (1995) developed a semiautomatic feedback control system for irrigation of basins and borders. A sensor at a downfield cutoff point was used to send an irrigation termination signal (via wire or infrared telemetry) to a controller at the upper end of the field. The semiautomatic control provided operator convenience and reduced water and labor use. Fekersillassie and Eisenhauer (2000a and 2000b) developed a model and operating criteria for feedback controlled surge irrigation primarily based upon runoff information because of difficulties in obtaining water advance information required for feedback control. Eisenhauer et al. (2000) conducted field studies to evaluate the performance of the feedback control model. In this study a runoff-measuring flume was placed at a single point at the downstream end of the field where the runoff exits the field and sixteen water advance sensors were placed in eight furrows in the left and the right halves of the field at one-fourth of the field length. Data was transmitted to the control system via infrared telemetry. The average deviation in effective irrigation depth was 3.0% and the maximum deviation from the mean was 10.8%. They also found that 32% of the furrows had not completed water advance during the planned advance phase and 7.5% had not completed advance after the entire irrigation. When using contact-type sensors manually positioned in the furrows Eisenhauer et al. (2000) observed that one of the main questions was where should the sensors be placed and how many sensors were needed? They determined that spatial and temporal variations in the infiltration rate were the most important factors in finding the optimum number of water advance sensors and their placements. Latimer and Reddell (1990) developed an automated system to control furrow irrigation. They sensed water advance at two predetermined locations in the furrow and determined infiltration parameters by using a volume balance equation that was then used in a model for management of the remainder of the irrigation event.

During the summer of 1995, Dr. Reddell of the Texas A&M University Agricultural Engineering Dept. conducted field tests of a furrow irrigation feedback control system based upon water arrival sensors placed in the furrows. The computed changes in water inflow were achieved by manual adjustment of the irrigation control valves. For the first experiment of irrigation into a

relatively dry profile a water savings of 60% (28 m^3 compared to 45 m^3 under normal practices) was achieved. In the second experiment, the irrigation was applied to relatively moist soil, a few days after a rain, 9 m^3 of water was applied under the controlled discharge compared to 22 m^3 under the normal practice of tail water. These field tests clearly show the advantages of feedback control of the water inflow with water application efficiencies in the range of 75 to 92 percent under feedback control as compared to a range of 30 to 55 percent under the normal constant inflow typically used in agriculture.

In 2004, we conducted a study at UC Davis to demonstrate the feasibility of automatic feedback control methods to the discharge of water into the furrow during the daytime using sunlight as the energy source and a visible light-based video camera and machine vision system to sense the leading edge of the advancing water in the furrows.

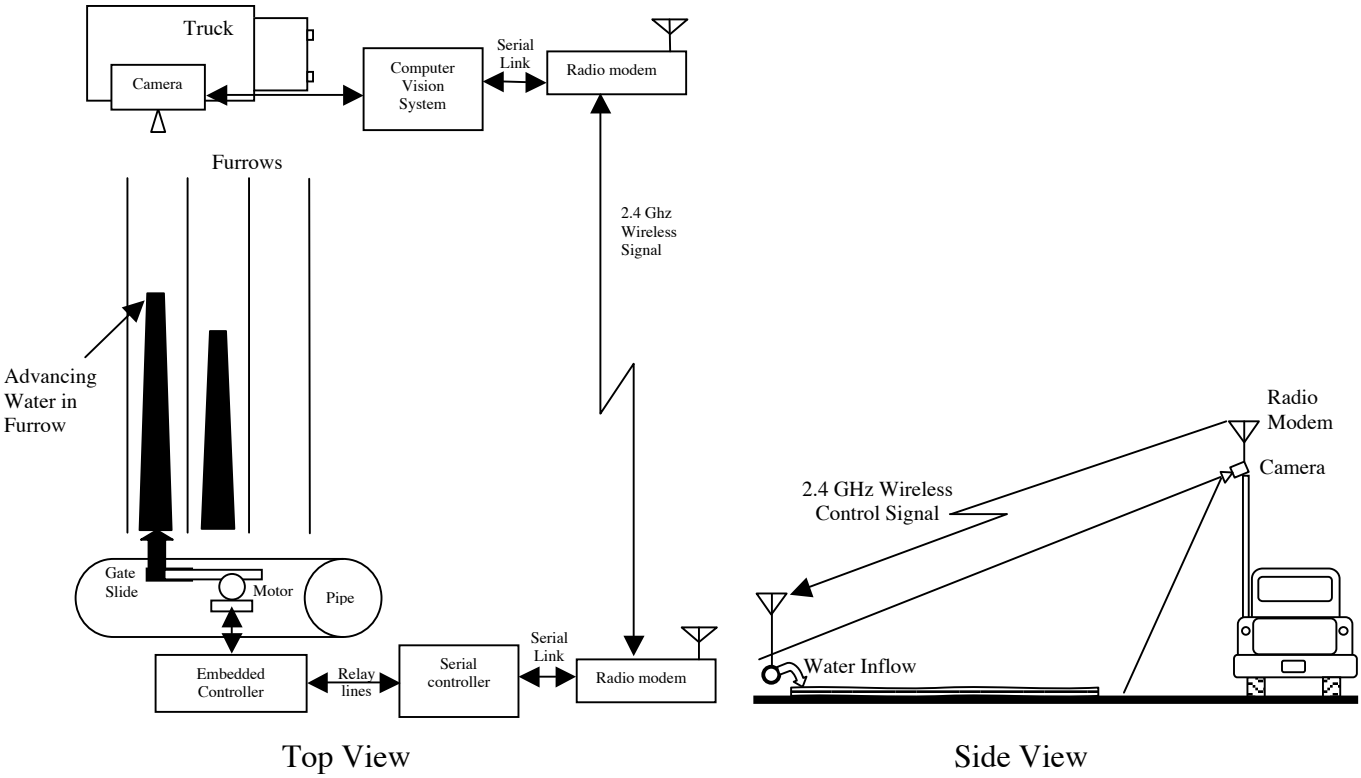


Figure 1. Schematic of automatic furrow irrigation discharge rate control system for daytime operation. Individual gate actuators on the gated pipe were controlled using a wireless radio signal from the video control system monitoring the advancing water in the furrow from the tail edge of the field.

The primary goals of this study were to demonstrate the feasibility of using ground-based remote sensing technology to measure water advance during the daytime and to demonstrate the feasibility of wireless control of the inflow rate to an individual furrow at the head edge of the

field from the control system located at the field edge at the tail end of the field. This project differed from other projects investigating irrigation feedback control where contact-type sensors are manually positioned in the furrows. It demonstrated that ground-based remote sensing of water advance can be done from the field boundary. A significant advantage of field-edge remote sensing is that it is compatible with tractor-based field operations (e.g. cultivation or chemical application) where contact-type sensors may need to be removed to avoid damaging them before a tractor could enter the field. Furthermore, a vision-based sensor offers the possibility of monitoring water advance over the length of the furrow with a single sensor, whereas multiple contact-type sensors must be placed in the furrow to monitor this same region. This system, demonstrated during the daytime in June 2004 at the UC Davis campus farm, captured visible images from a high mast mounted camera at the field edge. It located the leading edge of the advancing water in a selected furrow in each image. When the leading edge of the water reached a preset shut off distance, commands were sent via a wireless radio link to the gate controller at the other end of the field to shut the slide gate controlling inflow, Figure 1.

The general concept is that the camera moves perpendicular to the furrows along the tail edge of the field, monitoring the water advance in each furrow as it travels along the field boundary. Camera carriers such as tethered balloons, free flight radio controlled miniature aircraft, cable or rail transport or ground vehicle systems are possible transport methods for ground-based remote sensing of the water advance. Ultimately the carrier will be autonomous, guided by imaging alignment on row ends augmented by GPS and or other means such as buried cable, or a laser tracker with passive reflectors at row ends. On very large fields, multiple camera systems could be used in a mobile, self-organizing computer network to increase the update rate of feedback information for the automatic furrow irrigation control system.

A similar concept, known as networked infomechanical systems (NIMS) has been developed under a $7.5 million National Science Foundation grant to monitor a mountain stream or forest ecosystem looking for subtle changes in temperature, humidity or sunlight (http://www.engineeringalum.ucla.edu/magazine/nims.asp). NIMS was developed to provide systems that are self-aware and may autonomously adapt to their environment. Based upon a novel form of mobile embedded computing that exploits infrastructure, the system allows monitoring of full three-dimensional environments and the physical transport of diverse sensors and actuators. The NIMS prototype, called the Treebot due to its use within the forest canopy, is equipped with environmental sensors, a camera, a server and a wireless network link. It travels along a collection of steel cables, each attached to two tall trees. For example, the Treebot was suspended between two, tall Douglas fir trees at the Wind River Canopy Crane Research Facility (http://depts.washington.edu/wrccrf/NIMS/NIMS.html). The wireless network allows the system to transmit the data directly to computers in researchers' offices. The system docks when necessary to recharge its batteries, minimizing power constraints that have limited other remote wireless sensor networks in the past. Information learned about mobile sensing systems and remote wireless sensor networks from the NIMS study will be applied to our research on automatic furrow irrigation control.

While the 2004 UC Davis system successfully demonstrated the feasibility of automatic feedback control methods for furrow irrigation using ground-based remote sensing, the sensing system was limited to daytime operation. Thus there is a need to develop a ground-based remote

sensor that can detect the leading edge of water advance in irrigated furrows at night when the sensor is located at the field edge. Electromagnetic sensing methods are ideally suited for remote sensing of water in irrigated furrows due to their non-contact nature and ability to travel long distances quickly. In the visible portion of the electromagnetic spectrum, water at the shallow depth typically found in furrow irrigation is essentially transparent, figure 3. Water, at the temperatures typically found at night in an agricultural field, emits virtually no light in the visible region due to blackbody radiation. While moonlight or high-power light sources could be evaluated for use with the previously developed visible light sensing method; moonlight is not continuously available and high-power light sources are undesirable from an energy basis in a mobile sensing system. Thus a more energy efficient and commercially viable nighttime water sensor is desired for this application.

Researchers have studied many different methods of detecting water, either by itself (e.g. liquid water on the surface of a leaf) or as a component in a mixture (e.g. the moisture content of soil). Sensors are generally classified into one of two types, passive and active, based upon their energy requirements. A passive sensor does not require an additional energy source to measure the parameter of interest, while an active sensor requires an excitation signal that provides the necessary energy needed to make the measurement. For example, a standard visible light video camera is a passive sensor when operated outdoors during the daytime because the natural illumination is sufficient for video acquisition. However, in the dark (e.g. at nighttime on a moonless night) it becomes an active sensor because an external flash lamp is required to provide the necessary illumination. Research has shown that both passive and active sensing methods can be used for water detection.

While it is feasible to measure soil moisture (which has different properties from surface water in irrigated furrows) using a wide range of electromagnetic energy from high-energy x-ray to low energy radio waves, studies have shown that infrared and microwave energy bands are particularly advantageous for in situ measurements (Wheeler and Duncan, 1984; Upadhyaya et al., 1994). Remote sensing using satellite imaging can be used to distinguish bodies of water from surrounding surface features at night using passive thermal infrared and microwave imagery. For example, passive thermal infrared and microwave satellite imagery has been used to develop maps of sea ice in open seawater (Gloersen et al. 1992). The image appearance of a surface feature as obtained using passive thermal infrared and microwave radiometer depends on its emissivity (which is again dependent on incidence angle, frequency and polarization of the sensor) and its physical temperature.

The appearance of objects in a thermal infrared image is based upon three fundamental laws of physics: Wein's law, Kirchhoff's law, and the Stefan-Boltzmann law. Wein's law describes the relationship between the temperature, T, of a blackbody and the peak wavelength, λ_{Max}, of emitted electromagnetic radiation produced due to thermal radiation:

$$\lambda_{Max} = 2897.6\ \mu m\ K / T$$

For blackbodies in the range of temperatures normally found in an irrigated agricultural field, the peak wavelengths emitted range from 9 to 10 μm in the far (thermal) infrared region. The

Stefan-Boltzmann law describes the relationship between the total heat flow rate, Q, emitted from a blackbody of surface area A:

$$Q = A\varepsilon\sigma T^4$$

where ε is the emissivity and σ is the Stefan-Boltzmann constant. Kirchoff's law describes the emissivity, ε, of a material as the ratio of the radiant heat flow from an object made from that material to the radiant heat flow emitted from an ideal blackbody.

$$\varepsilon = Q_{Object} / Q_{Blackbody}$$

A blackbody (i.e. a perfect thermal emitter) has, by definition, an emissivity of 1. Water has a high emissivity ($\varepsilon_{Water} = 0.96$) making it a fairly good approximation of a blackbody, however the emissivity varies with the angle of observation. The emissivity is a maximum when viewed perpendicular to the water surface (i.e. as in a top view from a satellite) and remains fairly constant until the angle of observation is about 60 degrees from the surface normal and then begins to decrease (Wolfe and Zissis, 1978). Plant species have emissivities that range from 0.95 to 0.98 (Gates, 1964) and soil emissivities range from 0.90 to 0.98 (Idso and Jackson, 1969), however both are affected by moisture content.

Infrared thermometers or thermal imagers (satellite or aircraft) can be used to measure an object's surface temperature remotely. Both of these instruments measure the amount of radiation emitted from a surface and relate it to temperature using the three laws previously described. These methods can be used to detect crop water stress remotely by measurement of the crop's surface temperature. Silva et al. developed a real-time precision irrigation system based on the crop water stress index (CWSI) derived from infrared thermometry measurements. Infrared thermometers are a simple, convenient means to determine CWSI and thus monitor the crop water status (Idso et al. 1981; Jackson et al. 1981).

One of the unique properties of water is that it has a high specific heat capacity when compared to most dry materials. For comparison, water at 20 ºC has a specific heat capacity of 4181.8 J/kg·K while dry soil has a specific heat capacity of about 800 J/kg·K. Water tends to retain heat longer and to cool more slowly than materials with lower specific heat capacities. Dry soils tend to loose and gain heat fairly rapidly, because of their lower specific heat values. In the daytime water bodies are typically cooler than nearby dry bare soil or vegetative areas due to solar radiant heating. At night water bodies typically appear warm compared to meadows or dry bare soil, which appear cooler. Thus thermal sensors, including remote sensing using thermal imaging, can be effective in monitoring the movement of moisture in the environment. In satellite or airborne thermal imagery, where warm objects are bright and cool objects appear dark, the appearance of water bodies and dry bare soil follow a diurnal pattern, where the water is brighter that the surrounding soil at night and the reverse is true during the day.

A study of nighttime furrow temperature was conducted on the UC Davis campus farm to illustrate and confirm this temperature pattern under furrow irrigation. Two temperature probes were placed in a dry furrow about 200 feet from the tail end of the field and the temperature

recorded during irrigation at night. The resulting temperature profile shows the increase in temperature observed as the irrigation water reaches the temperature sensors, figure 2
In satellite or aircraft based remote sensing, microwave imagery is preferred to thermal infrared imagery because it is not hindered by cloud cover (Parkinson and Gloersen, 1993). In general, microwave-based imagery is not suited for high spatial resolution applications. Note that synthetic aperture radar, which takes advantage of the Doppler effect on moving satellites or airplanes to improve spatial resolution, is not applicable to the stationary ground-based remote sensing methods required in this proposal where real aperture system must be used. For stationary ground-based real aperture microwave imaging systems (SLAR), the spatial resolution of a microwave detector is defined as:

$\beta = \lambda/L$,

where β is the angular beam width of the detector in radians, L is the physical length of the microwave antenna and λ is the wavelength of the microwave radiation detected.

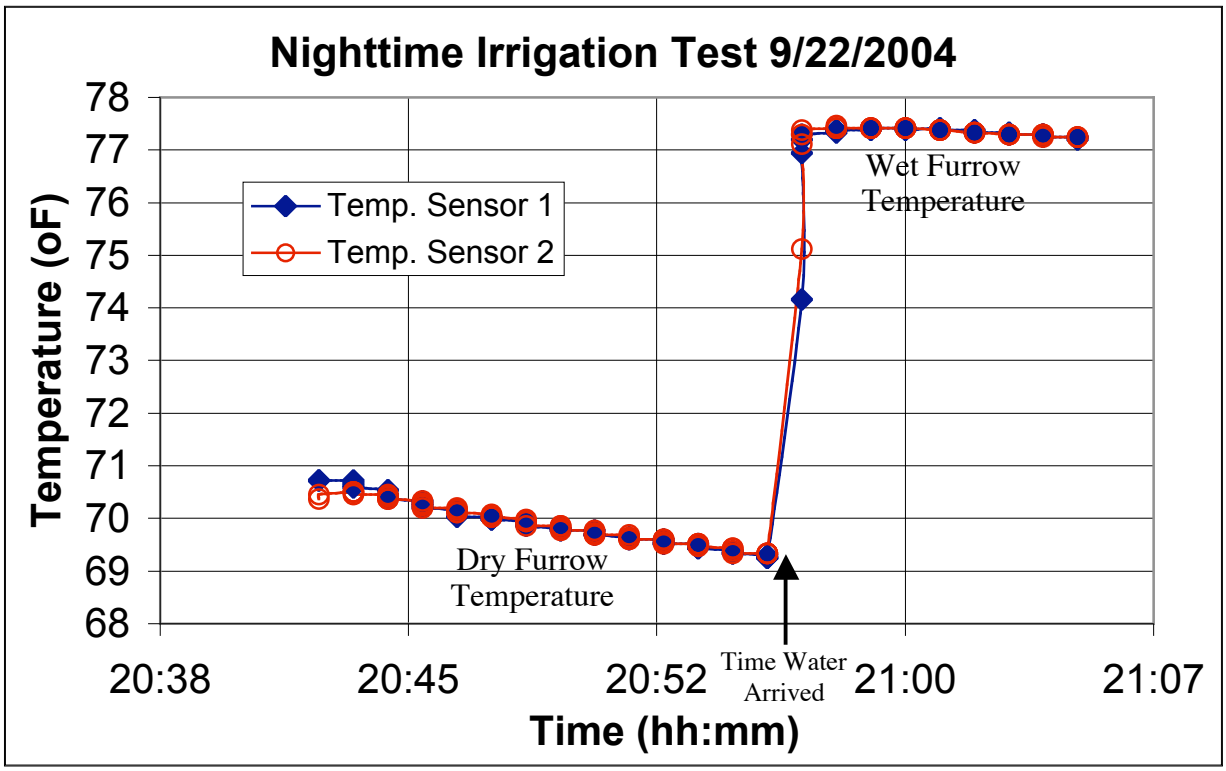


Figure 2. Nighttime furrow irrigation temperature results confirming remote sensing theory that furrow irrigation water will have a higher nighttime temperature than dry soil due to differences in specific heat. Tests conducted in experimental research plot on UC Davis campus farm, September 2004.

To detect a 10 cm (4 inch) wide water target in the bottom of a furrow 90 m (295 feet) from the field boundary requires a maximum beam width of about 0.001 radians. For the smallest wavelength (highest resolution) microwave (K-Band: $\lambda = 1.2$ cm) the length of microwave

antenna required for a resolution of 0.001 radians would be 10.9 m (36 feet), which is not very practical. In addition, microwave imaging systems are not readily available and their current cost makes them less attractive than other water detection methods. In a ground-based remote sensing application, cloud cover is not a problem and thermal infrared imagery is preferred to microwave systems due to lower cost and greater availability.

In addition to the passive thermal infrared methods described, water can be detected using active near infrared sensing methods. For example, Slaughter et al. (2001) demonstrated the feasibility of using near infrared spectroscopy to determine the moisture content of seven California soils. In the near infrared region (NIR: 700 to 2500 nm) the absorption of light is related to overtones and combinations of the natural frequencies of vibration of specific molecules. Materials such as water, soil and plant foliage have different chemical structures and thus they have different natural frequencies of vibration and their corresponding NIR spectra are different. For example, water has a strong absorption band at about 970 nm while the reflectance of soil or tomato foliage are fairly flat in this region, figure 3. These NIR differences can be used as the scientific basis of a sensor to detect the presence of water in the furrow of an agricultural field. Philipson and Hafker (1981) developed a ratio of the difference between visible reflectance and near infrared reflectance divided by visible reflectance to detect flooded versus unflooded regions using Landsat MSS imagery. The ratio was high for flooded areas (like water filled furrows) and low for dry soil areas in the image. Turbidity affected the use of infrared absorption to detect water by increasing the amount of light scattering decreasing the absorbance.

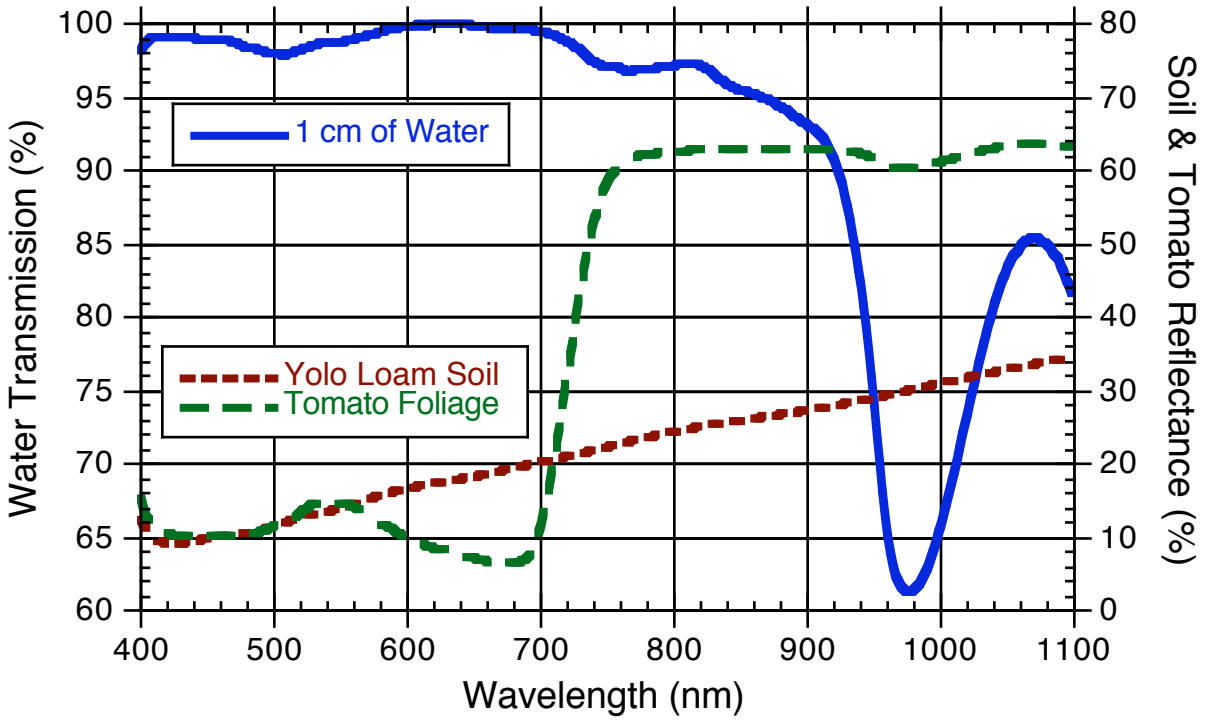


Figure 3 The transmission spectrum through 1 cm of water and the reflectance spectra of tomato foliage and soil in the visible and near infrared region up to 1100 nm.

Measurement of soil properties using changes in the state of polarization of electromagnetic waves has been tested in remote sensing using both passive and active approaches (Egan, 1985). Polarization of a nonpolarized light source and depolarization of a polarized light source by reflection on the soil surface were measured using light sources in the visible and infrared bands. Correlations have been established between the degree of polarization or depolarization and the incidence angle at a given incident light wavelength on different soil surfaces (Coulson, 1966; Egan and Hallock, 1969). Laboratory tests have demonstrated that, when a polarized laser is reflected by a soil surface, the reflected light is depolarized. The degree of depolarization generally decreases with an increase in moisture content of the soil sample (Zhang et al., 2000). The polarization technique has also been used for in-situ measurement of road surface-wetness (Itakura et al., 1982).

Objectives:

The primary objective of this proposed research is to develop non-contact sensing methods for the remote detection of water advance in row crop furrows during nighttime furrow irrigation. We will study the feasibility of using these water detection methods as feedback sensors in the automatic control of irrigation water in order to substantially improve water use efficiency in furrow irrigation by reducing water lost to deep percolation and tail water losses.

Specifically we will investigate the application of the following sensing methods for nighttime water detection:

1) passive thermal infrared sensors and
2) active near infrared laser-based sensors.

Statement of Work, Section 2: Technical/Scientific Merit, Feasibility

This research will consist of two primary tasks to study the feasibility of using 1) passive thermal infrared sensing methods, and 2) active near infrared sensing methods for the remote detection of water advance in row crop furrows during nighttime furrow irrigation.

Task 1: Development and Assessment of Passive Thermal Infrared Sensing Methods

The projected cost of task 1 is $324,314. Note that several of the supply and equipment items are common to tasks 1 and 2, and that there is some overlap in personnel activities between tasks that result in the total cost presented in Table C1 to be lower than the sum of the projected costs of each task when they are calculated as independent research projects.

1a: A thermal infrared image acquisition and image analysis system will be designed and constructed that is suitable for collection of ground-based remote images in an agricultural field. The system will be constructed from as many commercially available components possible, however, it is expected that some custom hardware and software components will need to be developed at UC Davis for this study.

1b: Compare the sensitivity of handheld point source thermal infrared sensors to low cost (i.e. uncooled) thermal imaging sensors to determine the feasibility of using uncooled thermal imaging sensors outdoors at the edge of an agricultural field to detect the presence of water in row crop furrows at night.

One of the main research questions regarding the use of thermal imaging cameras is whether the current technology has the required signal to noise ratio required to allow robust differentiation of thermal differences between soil and water. Thermal imaging cameras are currently available in two formats, cooled and uncooled, with cooled cameras currently costing two to eight times more than uncooled cameras. In addition to cost (which will likely come down over time), the other disadvantage of cooled cameras is their higher power requirement due to the power requirements of the cooling system itself. Automatic furrow irrigation control will have more rapid acceptance if the capital costs can be kept as low as possible.

Laboratory and field experiments will be designed (with appropriate statistical experimental design plans) and conducted to assess the thermal resolution of point source and imaging sensors over the range of temperatures expected in agricultural fields in California. Initial tests will be conducted in the laboratory with adjacent controlled temperature water baths. The laboratory tests will be conducted in a dark room to simulate nighttime conditions. The sensors will be mounted above the water surface with the optical axis parallel to the water surface normal. The laboratory tests will allow greater control of water temperature over a wider range of temperatures than the field tests. The laboratory results will be validated in the field using small experimental plots on the UC Davis campus farm. Water temperatures in the field will be controlled using mixtures of water of different temperatures to achieve the desired temperature conditions. Actual water and soil temperatures will be determined using temperature probes and computerized data loggers. Image processing and classification analysis will be

conducted to assess the sensitivity of the current thermal infrared technology in the detection of water in row crop furrows at night.

1c: Study the effect of angle of observation (with respect to the water surface normal) on the accuracy and precision of point source and imaging-based thermal infrared sensors.

As described in section 1, the emissivity of water varies with the angle of observation, with most of the change occurring at low angles. If tethered balloons or free flight radio controlled miniature aircraft are used to position the sensors then the angle of observation for most of the field will be within the range of uniform thermal emissivity. However, for cases where the detection system is placed about 4 or 5 meters above the ground at the edge of the field boundary, the angle of observation will be fairly low for most of the field and resulting in lower value of emissivity.

Laboratory and field tests will be designed (with appropriate statistical experimental design plans) and conducted to assess the affect of angle of observation on the accuracy and precision of point source and imaging-based thermal infrared sensors in determining absolute and relative temperature differences. Initial tests will be conducted in the laboratory with adjacent controlled temperature water baths using a range of temperatures expected in agricultural fields in California. The laboratory tests will be conducted in a dark room to simulate nighttime conditions. The laboratory results will be validated in the field using small experimental plots on the UC Davis campus farm. Water temperatures in the field will be controlled using mixtures of water of different temperatures to achieve the desired temperature conditions. Actual water and soil temperatures will be determined using temperature probes and computerized data loggers to validate non-contact temperature measurements.

1d: Characterize the level of soil/water surface thermal contrast in a row crop agricultural field at night over a range of environmental conditions throughout the normal processing tomato irrigation season found in northern California.

The success of remote thermal infrared detection depends upon adequate contrast between the objects of interest (soil and water in this case). There are several factors that can cause a thermal infrared apparent temperature difference. Of relevance to this study are: temperature, emissivity, and surface geometry. The emissivity is constant for a given material and moisture content. The surface geometry of soil can be affected by soil texture, tillage practices, moisture content, and compaction (wheel row versus non-wheel row). The surface geometry of water in irrigated furrows can be affected by wind and organic material floating in the water. Temperature is a function of the weather and a function of the time of the year and the time of the day or night.

Laboratory and field tests will be designed (with appropriate statistical experimental design plans) and conducted to assess the range of thermal contrast expected for a range of temperatures, emissivities, and surface geometries. A range of soil types common to California will be obtained from the UC Davis Land, Air and Water Resources Department. The soils will be conditioned with a range of moisture and compaction and simulated tillage treatments and their actual temperatures and apparent infrared temperatures determined in the laboratory. Field studies will be conducted to characterize the range of actual soil and water temperatures found at night throughout the normal

processing tomato irrigation season (March through September) on the UC Davis campus farm.

1e: Conduct alignment tests to align a laser rangefinder with the thermal infrared sensors in order to characterize the accuracy of distance measurements from the field boundary to the leading edge of water advance using laser range finding methods at night.

To provide the necessary feedback information for an automatic irrigation control system, the distance from the leading edge of water advance to the inflow at the pipe gate must be determined once the leading edge has been detected. Because the system must operate at night, the normal visual landmarks (e.g. row spacing) using in the daytime remote sensing system are unavailable. In this study a targetless commercial laser range finder will be used to determine the distance from the edge of the field to the leading edge of water advance detected by the infrared sensor. A custom mounting system will be designed and constructed to allow the physical alignment of the laser range finder with the optical axis of the thermal infrared sensors. Field studies will be designed (with appropriate statistical experimental design plans) and conducted to assess the accuracy of distance measurements from the field boundary to the leading edge of water advance using laser range finding methods at night. Actual distances will be determined using field tape measures or with reflective laser targets once their accuracy has been validated.

In the final year of the project, field studies will be conducted to document the expected gains in water application efficiency using remote thermal infrared sensors for feedback control of furrow irrigation. Field studies will be designed (with appropriate statistical experimental design plans) to measure both the furrow inflow rate (using a flow meter) as well as the rate of water advance (using the remote thermal infrared sensors). This data will be applied to existing furrow irrigation models to predict the impact on reductions in deep percolation and tail water losses using remote thermal infrared sensors.

Task 2: Development and Assessment of Active Near Infrared Sensing Methods

The projected cost of task 2 is $306,867 .

2a: A near infrared pulsed laser system and imaging detection system, with a peak wavelength near the 970 nm water absorption band will be designed and assembled from as many commercially available components possible, however, it is expected that some custom hardware and software components will need to be developed at UC Davis for this study. The system will be designed with industry standard safety interlocks and will use a rotating mirror system to allow laser scanning of the furrow.

2b: Study the effects of angle of polarization on the ability to distinguish the leading edge of water advance from dry soil in the furrow at night.

It is known that light reflected from the surface of water is highly polarized while that reflected from dry soil surfaces is almost unpolarized. Experiments will be designed (with appropriate statistical experimental design plans) and conducted to determine the effect of angle of polarization of a linearly polarized laser light source on the ability to distinguish the leading edge of water advance from dry soil in the furrow at night. Preliminary tests

will be conducted in a dark laboratory room and will be validated in the field if the preliminary results show positive results.

2c: Study the effect of angle of observation (with respect to the water surface normal) on the ability to use the optical absorbance at a single wavelength to the leading edge of water advance in the furrow at night.

The spectral data shown in figure 3 demonstrate that 970 nm light will be strongly absorbed by water (3 inches of water will absorb 98% of the light at 970 nm) and reflected by soil or plant foliage. Thus a 970 nm laser spot should be visible (using a near infrared camera) when pointed at the soil or on crop foliage, but should disappear when pointed at a few inches of water. Similar (but opposite in value of change) to the change in the emissivity with the angle of incidence, the reflectivity of light from the surface of water also varies with the angle of incidence. Thus, as the laser light scans down the furrow, both the reflectivity and the distance to the target changes, resulting in a possible change in reflectance. Laboratory and field experiments will be designed (with appropriate statistical experimental design plans) and conducted to assess feasibility of using a single wavelength near the 970 nm water absorption band to detect the difference between dry soil and water in furrows during irrigation at various angles of incidence. If preliminary results indicate that a single wavelength has inferior performance, a second laser at a different wavelength will be added to use as a reference to adjust for the effects of angle of incidence.

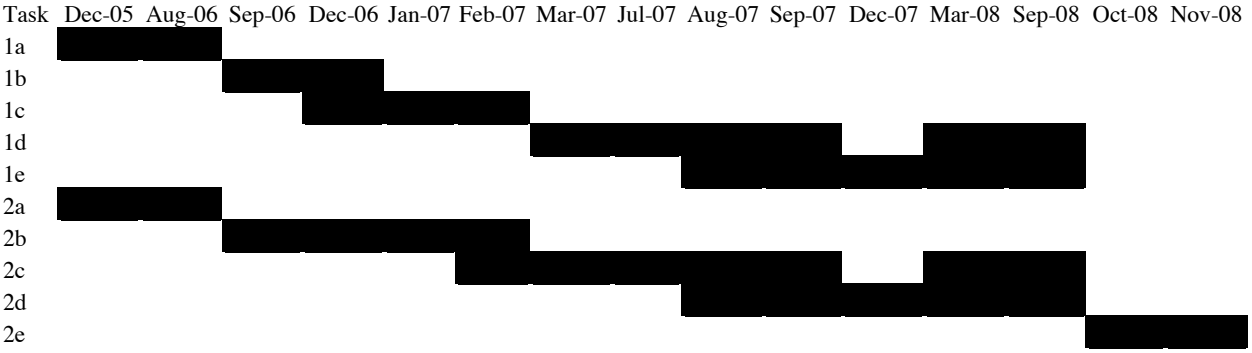
2d: Conduct alignment tests to align a laser rangefinder with the near infrared sensors in order to characterize the accuracy of distance measurements from the field boundary to the leading edge of water advance using laser range finding methods at night.

Similar to the thermal infrared case, it is necessary to determine the distance from the leading edge of water advance to the inflow at the pipe gate for adequate feedback control. A custom mounting system will be designed and constructed to allow the physical alignment of the laser range finder with the optical axis of the near infrared sensors. Field studies will be designed (with appropriate statistical experimental design plans) and conducted to assess the accuracy of distance measurements from the field boundary to the leading edge of water advance using laser range finding methods at night. Actual distances will be determined using field tape measures or with reflective laser targets once their accuracy has been validated.

In the final year of this project, field studies will be conducted to document the expected gains in water application efficiency using remote near infrared sensors for feedback control of furrow irrigation. Field studies will be designed (with appropriate statistical experimental design plans) to measure both the furrow inflow rate (using a flow meter) as well as the rate of water advance (using the remote near infrared sensors). This data will be applied to existing furrow irrigation models to predict the impact on reductions in deep percolation and tail water losses using remote near infrared sensors.

2e: Analyze data & compare the performance of the passive infrared method of Task 1 to the active method of Task 2 by applying remote sensing accuracies to existing furrow irrigation models to determine the impact on reductions in deep percolation and tail water losses. Write final report.

Work Schedule



Deliverables

At the end of the project we will provide the department of water resources with a final report that will contain the design specifications for a passive thermal infrared and an active near infrared remote sensing system for the nighttime detection of water in row crop furrows. We will also include an analysis of the accuracy and precision of the two sensing system as well as an assessment of the potential impact on reductions in deep percolation and tail water losses.

Environmental Documentation

As a research feasibility study, the study activities will be conducted in accordance with all federal, state and local laws and with the University of California environmental health and safety policies and regulations. Existing irrigation facilities and research structures on the UC Davis campus farm will be used for this study. No new structures or irrigation infrastructure will be constructed as a part of this study. Thus no local, county, State, or federal permits will be needed to conduct the study.

A “project” as defined by California Environmental Quality Act (CEQA), California Code of Regulations, Title 14, Division 6, Chapter 3, Section 15378 is:

"… the whole of an action, which has a potential for resulting in either a direct physical change in the environment, or a reasonably foreseeable indirect physical change in the environment...."

This research study does not meet the CEQA definition of a “project” requiring an environmental impact study. This proposed research feasibility study will not result in any direct or indirect physical change in the environment. The project will involve the use of conventional agricultural farming practices and data collection methods that have been used on the UC Davis campus research farm for many decades. There is no reason to believe that this proposed research will result in significantly different levels of direct or indirect physical change in the environment when compared to any prior row crop research project conducted on the UC Davis campus farm or from crop production methods used on any commercial farm in the Sacramento valley.

Statement of Work, Section 3: Monitoring and Assessment

- Explanation of the monitoring methodologies that will be used and the project monitoring data that will be collected to assess project results.

  Monitoring and assessment are an integral part of a properly conducted research project. Standard laboratory practices found in most research laboratories will be used in this project. These include the use of written laboratory notebooks where all aspects of the research are documented including: hypotheses and engineering design concepts, experimental (statistical and procedural) plans and engineering design alternatives, final engineering design plans, data logs and experimental observations. Project principal investigators will be in charge of monitoring project methodologies to verify that the research is being conducted according to accepted research practices, that appropriate experimental designs are utilized, that the data is collected in an accurate and organized manner, and that all appropriate safety procedures are being followed.

  Assessment of research results will be done using SAS and other appropriate computer software packages according to accepted statistical analysis techniques. Standard confidence limits (i.e. 95% and 99%), and levels of significance (i.e., 5% and1%) will be applied in the assessment of results. Bayesian classification techniques will be applied where appropriate and paired error analysis will be conducted to assess accuracy of paired distance measurements.
- Explanation of how the above data will be used to evaluate success in relation to project goals and objectives.

  For remote sensing objectives, project performance will be assessed in terms of classification accuracy rates in distinguishing water from soil and in terms of the distance error between the actual distance to the leading edge of water advance and that predicted by the remote sensing system. For overall water efficiency objectives, project performance will be evaluated by applying remote sensing accuracies to existing furrow irrigation models to determine the impact on reductions in deep percolation and tail water losses.

- Description of how pre-project conditions and data baselines will be determined, the basic assumptions being used, and the anticipated accuracy of the data to be produced.

  Where applicable, the pre-project conditions and data baselines will be assessed through the use of untreated controls in the experimental designs of affected research experiments. Basic assumptions will be based upon known physical properties of soil, water, plant materials, and knowledge of standard agricultural practices for crop production, including typical irrigation practices, as required in the design of experiments and remote sensing systems. It is expected that temperature data recorded in this study will be accurate to 1 ºC, with the exception of the uncooled thermal imaging system which may be slightly higher. It is expected that the actual distance measurements in the field will be accurate to within +/-0.5 feet and that the predicted distances from the remote sensing systems will be accurate to within +/- 5 feet.

- Description of how external factors such as changes in weather, cropping programs, or social conditions will be taken into account.

  External factors such as weather and cultural practices may have a significant impact of the performance of the remote sensing system and so these factors have been incorporated into the experimental designs developed to assess system performance. Aspects of the research that are affected by weather will be repeated in multiple years (within the time constraints of the proposal call) to give a more robust assessment of their impact.

- Information about how the data and other information will be handled, stored, and reported and made accessible to DWR and others.

  Data and other research information will be recorded in laboratory notebooks and stored on university computer systems. Important information will be made available to DWR and others in reports and journal publications and through UC cooperative extension sponsored field days and grower meetings.

- Estimated costs associated with the implementation of the monitoring and evaluation plan.

  As an integral part of the research, monitoring and evaluation costs are included in the project budget on page 21 .

Qualifications of the Applicants and Cooperators

Resumes for professors Slaughter, Wallender, and Upadhyaya are attached to the end of the proposal.

Professor Slaughter is an expert in instrumentation, sensor development and robotics. He has conducted considerable research on the use of optics and machine vision in agricultural applications and has a US patent on a machine vision guidance system for use in precision cultivation of processing tomatoes and other California row crops. He developed the optical inspection system used at all California processing tomato inspection stations. This system is used to determine the color quality of all processing tomatoes grown in California. Together with professor Upadhyaya, he has developed a near infrared sensing method for the determination of moisture for California soils and they are currently working on an infrared method for determining soil nitrogen content.

Professor Wallender is an expert in hydrology, irrigation engineering, modeling and the statistical description of irrigation system performance including drainage reduction through irrigation system control. He has considerable experience in geographic information systems and in the use of remote sensing for regional water and land management applications.

Professor Upadhyaya is an expert in precision agriculture technology including GPS and GIS, in tillage, soil dynamics and the modeling of biological systems. He has considerable expertise in the design and development of soil property and crop yield sensors. Together with professor Slaughter, he has developed a near infrared sensing method for the determination of moisture for California soils and they are currently working on an infrared method for determining soil nitrogen content.

Outreach, Community Involvement and Acceptance

The University of California has an excellent system for the dissemination of agricultural research results through the outreach programs offered by its cooperative extension specialists and farm advisors. This study will fully utilize these programs and will disseminate the research findings through local grower meetings, and on-campus field days organized by cooperative extension specialists and farm advisors. Research findings will also be presented at national and international conferences on precision agriculture. In addition, research findings will be published and made available to the public through printed sources such as California Agriculture and the Transactions of the American Society of Agricultural Engineers.

Innovation

This proposed project seeks to develop state-of-the-art ground-based remote sensing technology for the remote detection of water advance in row crop furrows during nighttime furrow irrigation. These innovative water detection methods will be used as feedback sensors in the automatic control of irrigation water in order to substantially improve water use efficiency in furrow irrigation by reducing water lost to deep percolation and tail water losses. Because

furrow irrigation is the most popular method of row crop irrigation throughout California these new sensing technologies could be used to substantially improve the water use efficiency if applied to furrow irrigation in all of California.

Benefits and Costs

Project costs (both in total and by year) are shown in Table C-1 on the following four pages.

Labor costs

Support is requested in the amount of $209,282 ($66,386 in year 1, $69,705 in year 2 and $73,191 in year 3) for a 100% time Post Doctoral Scholar; 50% time academic year, 100% time summer Graduate Student Researcher III; 25% time academic year, 100% time summer Undergraduate Student Asst. IV; and 10% time Development Engineer to conduct the proposed research. Fringe benefits are calculated at 30% for the Post Doctoral Scholar, 3% for the Graduate Student Researcher, 3% for the Undergraduate Student Asst. IV, and 32% for the Development Engineer. Graduate fee remission of $26,503 ($8,407 in year 1, $8827 in year 2, and $9269 in year 3) is requested in support of the Graduate Student Researcher.

Equipment costs

Funds of $25,300 for a thermal infrared imaging system and a near infrared laser range finder are requested in year 1.

Supply costs

Support is requested in the amount of $56,160 ($37,455 in year 1, $9,125 in year 2, and $9,580 in year 3) for supplies and materials including: lasers, polarizing and interference filters & optical components and mounting fixtures, IR temperature sensors and data loggers, lenses, IR safety goggles, NIR vision system (camera & computer), optical encoders, software, electronic and mechanical fabrication supplies, irrigation field support, field supplies and publication costs.

Travel costs

Support is requested in the about of $6,855 ($1,540 in year 1, $1,617 in year 2, and $3,698 in year 3) for travel by UCD project researchers to conduct experiments and present results at scientific meetings.

Indirect costs

Indirect costs are $77,704 for this three-year project, which is calculated as 25% of the UC Davis modified direct costs (exclusive of equipment and fee remission).

Potential benefits and information to be gained in terms of water use efficiency:

Both tail water runoff and deep percolation will be reduced under surface irrigation using this remote sensing approach. In most water and irrigation districts of California's Central Valley, no tail water is allowed to either leave a ranch or a district whereas in Imperial Valley there is no such restriction. In the latter case of tail water runoff, the water savings are as much as 20 percent of applied water which, if prevented, translates into significant improvements in water use efficiency. Deep percolation will be decreased by using the maximum advance rate to spread the water quickly across the field. In the Coachella Valley (no tailwater) the losses to deep percolation are in the neighborhood of 40% of applied water while in the Central Valley they are much less but not zero. Again by reducing these losses the water use efficiency will improved dramatically. Prior research on in-furrow contact sensors, has shown that a more than a 5% water savings is achievable if automatic feedback control is used in furrow irrigation.

The benefits of water savings accrue at the rate of about $40 per acre foot of water saved, of course depending on local conditions. Chapters 11 and 12 of the draft California Water Plan (http://www.waterplan.water.ca.gov/b160/workgroups/chapterreviewgroup.htm) show that tailwater losses due to surface irrigation to the Salton Sea in the Colorado River Hydrologic Region (which includes the Coachella and Imperial valleys) are about 1 million acre feet annually with additional losses to deep percolation of about 85 thousand acre feet annually, of which 10% or more is attributable to furrow irrigation. In the Sacramento - San Joaquin Delta region about 546 thousand acre feet of water is applied annually in row crops. If a 5% water savings were achieved using remote sensing feedback, it would results in an annual savings of about 33 thousand acre feet annually. Over the three year period of this proposal the potential savings would be in excess of $4 million. This benefit (avoided cost) is much greater than the cost of this research project or the anticipated cost of the new technology.

PROJECT IMPLEMENTATION COSTS TABLES

APPLICANT: David Slaughter, University of California, Davis

Project Title: Ground-based Remote Sensing Technology for Improved Agricultural Water use Efficiency in Furrow Irrigation Systems.

Table C-1: Project Costs (Total Budget)

	Category (I)	Project Costs $ (II)	Contingency % (ex. 5 or 10) (III)	Project Cost + Contingency $ (IV)	Applicant Share $ (V)	State Share Grant $ (VI)	Life of investment (years) (VII	Capital Recovery Factor (VIII)	Annualized Costs $ (IX)
	Administration[1]								
	Salaries, wages	$209,282	5	$219,746	$0	$219,746	0	0.0000	$0
	Fringe benefits	$65,023	5	$68,274	$0	$68,274	0	0.0000	$0
	Supplies	$56,160	5	$58,968	$0	$58,968	0	0.0000	$0
	Equipment	$25,300	5	$26,565	$0	$26,565	0	0.0000	$0
	Consulting services	$0	0	$0	$0	$0	0	0.0000	$0
	Travel	$6,855	5	$7,198	$0	$7,198	0	0.0000	$0
	Other (25% UCD Overhead)	$77,704	5	$81,589	$0	$81,589	0	0.0000	$0
(a)	Total Administration Costs	$440,324		$462,340	$0	$462,340			$0
(b)	Planning/Design/Engineering	$0	0	$0	$0	$0	0	0.0000	$0
(c)	Equipment Purchases/ Rentals/Rebates/Vouchers	$0	0	$0	$0	$0	10	0.0000	$0
(d)	Materials/Installation/Implementation	$0	0	$0	$0	$0	0	0.0000	$0
(e)	Implementation Verification	$0	0	$0	$0	$0	0	0.0000	$0
(f)	Project Legal/License Fees	$0	0	$0	$0	$0	0	0.0000	$0
(g)	Structures	$0	0	$0	$0	$0	0	0.0000	$0
(h)	Land Purchase/Easement	$0	0	$0	$0	$0	0	0.0000	$0
(i)	Environmental Compliance/ Mitigation/Enhancement	$0	0	$0	$0	$0	0	0.0000	$0
(j)	Construction	$0	0	$0	$0	$0	0	0.0000	$0
(k)	Other (Specify)	$0	0	$0	$0	$0	0	0.0000	$0
(l)	Monitoring and Assessment	$0	0	$0	$0	$0	0	0.0000	$0
(m)	Report Preparation	$0	0	$0	$0	$0	0	0.0000	$0
(n)	**TOTAL**	$440,324		$462,340	$0	$462,340			$0
(o)	Cost Share -Percentage				0	100			

1 (Excludes administration O & M costs)

APPLICANT: David Slaughter, University of California, Davis
Project Title: Ground-based Remote Sensing Technology for Improved Agricultural Water use Efficiency in Furrow Irrigation Systems.

Table C-1: Project Costs (Year 1 Budget)

	Category (I)	Project Costs $ (II)	Contingency % (ex. 5 or 10) (III)	Project Cost + Contingency $ (IV)	Applicant Share $ (V)	State Share Grant $ (VI)	Life of investment (years) (VII	Capital Recovery Factor (VIII)	Annualized Costs $ (IX)
	Administration[1]								
	Salaries, wages	$66,386	5	$69,705	$0	$69,705	0	0.0000	$0
	Fringe benefits	$20,626	5	$21,657	$0	$21,657	0	0.0000	$0
	Supplies	$37,455	5	$39,328	$0	$39,328	0	0.0000	$0
	Equipment	$25,300	5	$26,565	$0	$26,565	0	0.0000	$0
	Consulting services	$0	0	$0	$0	$0	0	0.0000	$0
	Travel	$1,540	5	$1,617	$0	$1,617	0	0.0000	$0
	Other (25% UCD Overhead)	$29,400	5	$30,870	$0	$30,870	0	0.0000	$0
(a)	Total Administration Costs	$180,707		$189,742	$0	$189,742			$0
(b)	Planning/Design/Engineering	$0	0	$0	$0	$0	0	0.0000	$0
(c)	Equipment Purchases/ Rentals/Rebates/Vouchers	$0	0	$0	$0	$0	10	0.0000	$0
(d)	Materials/Installation/Implementation	$0	0	$0	$0	$0	0	0.0000	$0
(e)	Implementation Verification	$0	0	$0	$0	$0	0	0.0000	$0
(f)	Project Legal/License Fees	$0	0	$0	$0	$0	0	0.0000	$0
(g)	Structures	$0	0	$0	$0	$0	0	0.0000	$0
(h)	Land Purchase/Easement	$0	0	$0	$0	$0	0	0.0000	$0
(i)	Environmental Compliance/ Mitigation/Enhancement	$0	0	$0	$0	$0	0	0.0000	$0
(j)	Construction	$0	0	$0	$0	$0	0	0.0000	$0
(k)	Other (Specify)	$0	0	$0	$0	$0	0	0.0000	$0
(l)	Monitoring and Assessment	$0	0	$0	$0	$0	0	0.0000	$0
(m)	Report Preparation	$0	0	$0	$0	$0	0	0.0000	$0
(n)	**TOTAL**	$180,707		$189,742	$0	$189,742			$0
(o)	Cost Share -Percentage				0	100			

1 (Excludes administration O & M costs)

APPLICANT: David Slaughter, University of California, Davis
Project Title: Ground-based Remote Sensing Technology for Improved Agricultural Water use Efficiency in Furrow Irrigation Systems.

Table C-1: Project Costs (Year 2 Budget)

	Category (I)	Project Costs $ (II)	Contingency % (ex. 5 or 10) (III)	Project Cost + Contingency $ (IV)	Applicant Share $ (V)	State Share Grant $ (VI)	Life of investment (years) (VII	Capital Recovery Factor (VIII)	Annualized Costs $ (IX)
	Administration[1]								
	Salaries, wages	$69,705	5	$73,190	$0	$73,190	0	0.0000	$0
	Fringe benefits	$21,657	5	$22,740	$0	$22,740	0	0.0000	$0
	Supplies	$9,125	5	$9,581	$0	$9,581	0	0.0000	$0
	Equipment	$0	5	$0	$0	$0	0	0.0000	$0
	Consulting services	$0	0	$0	$0	$0	0	0.0000	$0
	Travel	$1,617	5	$1,698	$0	$1,698	0	0.0000	$0
	Other (25% UCD Overhead)	$23,319	5	$24,485	$0	$24,485	0	0.0000	$0
(a)	Total Administration Costs	$125,423		$131,694	$0	$131,694			$0
(b)	Planning/Design/Engineering	$0	0	$0	$0	$0	0	0.0000	$0
(c)	Equipment Purchases/ Rentals/Rebates/Vouchers	$0	0	$0	$0	$0	10	0.0000	$0
(d)	Materials/Installation/Implementation	$0	0	$0	$0	$0	0	0.0000	$0
(e)	Implementation Verification	$0	0	$0	$0	$0	0	0.0000	$0
(f)	Project Legal/License Fees	$0	0	$0	$0	$0	0	0.0000	$0
(g)	Structures	$0	0	$0	$0	$0	0	0.0000	$0
(h)	Land Purchase/Easement	$0	0	$0	$0	$0	0	0.0000	$0
(i)	Environmental Compliance/ Mitigation/Enhancement	$0	0	$0	$0	$0	0	0.0000	$0
(j)	Construction	$0	0	$0	$0	$0	0	0.0000	$0
(k)	Other (Specify)	$0	0	$0	$0	$0	0	0.0000	$0
(l)	Monitoring and Assessment	$0	0	$0	$0	$0	0	0.0000	$0
(m)	Report Preparation	$0	0	$0	$0	$0	0	0.0000	$0
(n)	**TOTAL**	$125,423		$131,694	$0	$131,694			$0
(o)	Cost Share -Percentage				0	100			

1 (Excludes administration O & M costs)

APPLICANT: David Slaughter, University of California, Davis
Project Title: Ground-based Remote Sensing Technology for Improved Agricultural Water use Efficiency in Furrow Irrigation Systems.

Table C-1: Project Costs (Year 3 Budget)

	Category (I)	Project Costs $ (II)	Contingency % (ex. 5 or 10) (III)	Project Cost + Contingency $ (IV)	Applicant Share $ (V)	State Share Grant $ (VI)	Life of investment (years) (VII	Capital Recovery Factor (VIII)	Annualized Costs $ (IX)
	Administration[1]								
	Salaries, wages	$73,191	5	$76,851	$0	$76,851	0	0.0000	$0
	Fringe benefits	$22,740	5	$23,877	$0	$23,877	0	0.0000	$0
	Supplies	$9,580	5	$10,059	$0	$10,059	0	0.0000	$0
	Equipment	$0	5	$0	$0	$0	0	0.0000	$0
	Consulting services	$0	0	$0	$0	$0	0	0.0000	$0
	Travel	$3,698	5	$3,883	$0	$3,883	0	0.0000	$0
	Other (25% UCD Overhead)	$24,985	5	$26,234	$0	$26,234	0	0.0000	$0
(a)	Total Administration Costs	$134,194		$140,904	$0	$140,904			$0
(b)	Planning/Design/Engineering	$0	0	$0	$0	$0	0	0.0000	$0
(c)	Equipment Purchases/ Rentals/Rebates/Vouchers	$0	0	$0	$0	$0	10	0.0000	$0
(d)	Materials/Installation/Implementation	$0	0	$0	$0	$0	0	0.0000	$0
(e)	Implementation Verification	$0	0	$0	$0	$0	0	0.0000	$0
(f)	Project Legal/License Fees	$0	0	$0	$0	$0	0	0.0000	$0
(g)	Structures	$0	0	$0	$0	$0	0	0.0000	$0
(h)	Land Purchase/Easement	$0	0	$0	$0	$0	0	0.0000	$0
(i)	Environmental Compliance/ Mitigation/Enhancement	$0	0	$0	$0	$0	0	0.0000	$0
(j)	Construction	$0	0	$0	$0	$0	0	0.0000	$0
(k)	Other (Specify)	$0	0	$0	$0	$0	0	0.0000	$0
(l)	Monitoring and Assessment	$0	0	$0	$0	$0	0	0.0000	$0
(m)	Report Preparation	$0	0	$0	$0	$0	0	0.0000	$0
(n)	**TOTAL**	$134,194		$140,904	$0	$140,904			$0
(o)	Cost Share -Percentage				0	100			

1 (Excludes administration O & M costs)

References

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Education

1987 - Ph.D. awarded in Agricultural Engineering, University of Florida. Dissertation title "Color Vision for Robotic Orange Harvesting".

1984 - M.S. awarded in Biological and Agricultural Engineering, North Carolina State University.

1982 - B.S. awarded with high honors in Agricultural Engineering, University of California, Davis.

Employment

1996 - Present Associate Professor, Department of Biological and Agricultural Engineering, University of California, Davis.

1990 - 1996 Assistant Professor, Department of Biological and Agricultural Engineering, University of California, Davis.

1987-1990 Research Scientist, Instrumentation and Sensing Laboratory, USDA - Agricultural Research Service, Beltsville, MD.

1984-1987 Research Scientist, Insect Attractants, Behavior, and Basic Biology Research Laboratory, USDA - Agricultural Research Service, Gainesville, FL.

Honors and Awards

1998 - American Society of Agricultural Engineers Paper Award for publication titled "Precision band spraying with machine vision guidance and adjustable yaw nozzles".
1997 - American Society of Agricultural Engineers Paper Award for publication titled "Machine vision detection of early split pistachio nuts".
1990 - American Society of Agricultural Engineers Paper Award for publication titled "Discriminating fruit for robotic harvest using color in natural outdoor scenes."
1989 - USDA Certificate of Merit.
1986 - USDA Certificate of Merit and Quality Increase.
1984 - USDA Engineering Traineeship
1982 - American Society of Engineers Student Honor Award.
1981 - Robert Row Owen Academic Scholarship.
1979 - Ben L. Hagglund Academic Scholarship.

Professional and Honorary Societies

Alpha Epsilon - Agricultural Engineering Honor Society.
American Society of Agricultural Engineers.
Council for Near Infrared Spectroscopy.
Phi Kappa Phi - National Interdisciplinary Honor Society.
Pi Mu Epsilon - National Honorary Mathematics Fraternity.
Sigma Xi - Scientific Research Society
Tau Beta Pi - National Engineering Honor Society

Patents

Slaughter, D.C., R. Curley, P. Chen, and D.K. Giles. 1995. Robotic Cultivator. U.S. Patent No. 5,442,552.

Giles, D. K., and D. C. Slaughter. 1996. Adjustable spray system and assembly method. U.S. Patent No. 5,544,813. August 13, 1996. (Similar Canadian Patent Pending). Licensed to Capstan Ag Systems, Inc., Topeka, KS.

Selected Publications

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Tian, L., D.C. Slaughter, and R.F. Norris. 1997. Outdoor field machine vision identification of tomato seedlings for automated weed control. Transactions of the ASAE 40(6):1761-1768.

Li, M., D.C. Slaughter, and J.F. Thompson. 1997. Optical chlorophyll sensing system for banana ripening. Postharvest Biology and Technology 12:273-283.

Sebben, E., D.C. Slaughter, and R.P. Singh. 1998. Optical assessment of corn oil deterioration during frying. J. of Food Processing and Preservation 22(4):265-282.

Tian, L.F., and D.C. Slaughter. 1998. Environmentally adaptive segmentation algorithm for outdoor image segmentation. Computers and Electronics in Agriculture. 21:153-168.

Ehsani, M.R., S.K. Upadhyaya, D. Slaughter, S. Shafii, and M. Pelletier. 1999. A NIR technique for rapid determination of soil mineral nitrogen. Precision Agriculture. 1(2):217-234.

Slaughter, D.C., C.G. Cavaletto, L.D. Gautz, and R.E. Paull, 1999. Non-destructive determination of soluble solids in papayas using near infrared spectroscopy.

Slaughter, D.C., M.G. Pelletier, and S.K. Upadhyaya. 2001. Sensing soil moisture using NIR spectroscopy. Applied Engineering in Ag. 17(2): 241–247

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Downey, D., D.K. Giles and D.C. Slaughter. 2004. Mapping weeds using DGPS and ground based vision identification. California Agriculture. 58(4):218-221.

M. Nielsen, H. J. Andersen, D. C. Slaughter, D. K. Giles 2004. Detecting leaf features for automatic weed control using trinocular stereo vision. Proc. 7th International Conference on Precision Agriculture and Other Precision Resources Management. Minneapolis.

Haff, R.P., and D.C. Slaughter. 2004. Real-time x-ray inspection of wheat for infestation by the granary weevil, *Sitophilus Granarius* (L.). Trans. of the ASAE. Vol. 47(2): 531-537.

Giles, D.C. Slaughter, D. Downey, J.C. Brevis-Acuna, W.T. Lanini. 2004. Application design for machine vision guided selective spraying of weeds in high value crops. Aspects of Applied Biology. 71(1): 75-81.

Curriculum Vitae

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EDUCATION AND REGISTRATION

Ph.D. Utah State University, Engineering, June 1982.
M.S. University of California Davis, Water Science, June 1978
B.S. Utah State University, Agricultural and Irrigation Engineering, September 1981
B.S. Oregon State University, Agricultural Engineering Technology, June 1976
EIT Engineer-in-Training Exam, May 1979
PE Professional Engineer, California, 1987

WORK EXPERIENCE

1982-present. Assistant-82-88, Associate-88-92 and Full-Professor-92-present, University of California Davis. Research includes modeling and measurement of precipitation- and irrigation-driven watersheds from submeter to kilometer scales. Specific subject matter interest includes water, energy and chemical transport for sustainable agroecosystems. Teach undergraduate courses in fluid mechanics, GIS and spatial analysis, and irrigation system design and graduate courses in continuum mechanics as well as surface irrigation hydraulics. Funding in excess of $6 million supporting the completion of 30 graduate student theses. More than 110 refereed journal articles and book chapters.

1992-3. Director, University of California Salinity/Drainage Research Program. Administered the development, interpretation, and dissemination of research knowledge addressing critical environmental problems on salinity, drainage, selenium, and other toxic elements in the San Joaquin Valley. Initiated a long term study on the sustainability of irrigated agroecosystems within environmental constraints.

1980-2. Consultant to Keller Engineering, Logan, UT. Measured and analyzed mine wastewater disposal. Conducted infiltration tests to design pressurized irrigation systems.

1987-present. Registered Profession Engineering Consultant. Advise watershed entities in California. Advice and consulting to governments of France, Egypt, Oman, Mexico, Morocco, China, Brazil, and India and to the International Rice Research Institute (Philippines) and the International Water Management Institute (Sri Lanka).

PROFESSIONAL, SCIENTIFIC, HONORARY SOCIETIES AND AWARDS

American Geophysical Union, American Society of Agricultural Engineers, American Society of Civil Engineers
Who's Who Among Students in American Universities and Colleges, Phi Kappa Phi, Sigma Xi, Alpha Zeta, Tau Beta Pi, Blue Key
Who's Who in California, 1998
Who's Who in Engineering Education, 2002
External Reviewer (3), Ph.D. Dissertation, Indian Institute of Technology
American Society of Civil Engineers, Best Practices Paper Award, 2002.
American Society of Civil Engineers, Best Research Paper Award, 2003.
American Society of Agricultural Engineers, Technical Reviewer Special Recognition, 2001, 2002
Distinguished Alumnus Award, Utah State University, College of Engineering (BIE), 2004

MEMBERSHIP ON COMMITTEES AND EDITORIAL BOARDS

Editor, Soil and Water Division, American Society of Agricultural Engineers, 2004-present
Associate Editor, Soil and Water Division, American Society of Agricultural Engineers, Developed and implemented procedures for an electronic journal, 1991-present

Member, Advisory Board, International Journal of Water Resources Engineering, 1991-present
Member, Editorial Board, Irrigation Science, 1994-present
Member, Editorial Board, Brazilian Journal of Irrigation and Drainage, 2002-present
Member, Technical Advisory Committee on Forest Geology, State of California Mining and Geology Board, 2002-present
Member, Challenge Program Consortium, Global Challenge Program on Food and Water, Consultative Group on International Agricultural Research, 2001-2
Member, Integrated Basin Water Management Systems (Research) Workgroup, Global Challenge Program on Food and Water, Consultative Group on International Agricultural Research, 2001-2

RECENT REFEREED PUBLICATIONS

99. Wallender, W.W. and M.E. Grismer. 2002. Irrigation hydrology-Crossing scales. J. of Irrigation and Drainage Engineering ASCE 128(4):203-211.
100. Kumar, M., N.S. Raghuwanshi, R. Singh, W.W. Wallender, and W.O. Pruitt. 2002. Estimating evapotranspiration using artificial neural networks. J. of Irrigation and Drainage Engineering ASCE 128(4):223-233.
101. Young, C.A. and W. W. Wallender. 2002. Spatially distributed irrigation hydrology: water balance. Transactions of the American Society of Agricultural Engineer 45(3):609-618.
102. Zalom, F. G., M. N. Oliver, W. W. Wallender, I. Werner, B. W. Wilson, W. H. Krueger, B. T. Angermann, L. A. Deanovic, T. S. Kimball, J. D. Henderson, G. H. Oliveira, and P. Osterli. 2002. Monitoring and mitigating offsite movement of dormant spray pesticides from California orchards. Acta Horticulturae. 592:729-735.
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106. Wallender, W.W., J. Rhoades, M. Weinberg, S. Lee and C. Uptain. 2002. Irrigated land retirement. Irrigation and Drainage Systems 16:311-326.
107. Buyuktas, D. and W.W. Wallender. 2004. Dispersion in spatially periodic porous media. Heat and Mass Transfer Research Journal 40 (2004):261-270.

108. Joyce, Brian, W. W. Wallender, T. Angermann, B.W. Wilson, I. Werner, M.N. Oliver, F.G. Zalom, and J.D. Henderson. 2004. Using infiltration enhancement and soil water management to reduce Diazinon in runoff. Journal of the American Water Resources Association. August: 1063 – 1070.
109. Sivakumar, B., W.W. Wallender, C.E. Puente, and M.N. Islam. 2004. Streamflow disaggregation: a nonlinear deterministic approach. Nonlinear Processes in Geophysics. 11: 383-392
110. Vrugt, J.A., G. Schoups, J.W. Hopmans, C.A. Young, W.W. Wallender, T.A. Harter and W. Bouten. 2004. Inverse modeling of large-scale distributed vadose zone properties using global optimization. Water Resources Research, Vol. 40: 1-20.
111. Purkey, D.R. W.W. Wallender, G.E. Fogg, and B. Sivakumar. 2004. Describing near surface, transient flow processes in unconfined aquifers below irrigated lands: model application in the western San Joaquin valley, California. Journal of Irrigation and Drainage Engineering 130:451-459.
112. Werner, I., F.G. Zalom, M.N. Oliver, L.A. Deanovic, T.S. Kimball, J.D. Henderson, B.W. Wilson, W. Krueger, and W.W. Wallender. 2004. Toxicity of stormwater runoff after dormant spray application in a French prune orchard (Glenn county, California, USA): temporal patterns and the effect of ground covers. Environmental Toxicology and Chemistry 23(11):2719-2726.

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Ph.D. (1979)	Agr. Eng., Cornell University, Ithaca, New York
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B.Tech.(Hons)(1972)	Agr. Eng., IIT, Kharagpur, West Bengal, India

RESEARCH INTEREST:

Precision farming or SSCM, Sensor development, Instrumentation, GPS, GIS, Soil dynamics, Soil compaction and Infiltration, Machinery design, Variability and mapping.

WORK EXPERIENCE:

July 1992 to Present	Professor, Dept. of Bio. and Agr. Eng. Dept., UC Davis.
July 1987 - June 1992	Associate Professor, Dept. Bio.and Agr. Eng. Dept., UC Davis.
Sept. 1983 - June 1987	Assistant Professor, Dept. Bio. and Agr. Eng. Dept., UC Davis.
Sept. 1981 - Aug. 1983	Assistant Professor, Dept. Agri. Eng., Univ. of Del., Newark, DE
Jan. 1979 - Aug. 1981	Research Associate, Dept. Agr. Eng., Cornell University, Ithaca, NY.

PATENT: 1. Hydro-Pneumatic Seed Singulation for Plant Propagules US Patent 4917029.
2. Method and apparatus for ultra precise GPS based mapping of seeds or vegetation during planting – Patent No: US 6516271B2.
3. Upadhyaya, S. K., M. Ehsani, and M. L. Mattson. 2003. Method and apparatus for ultra precise GPS-based mapping of seeds or vegetation during planting. US patent No. **6,553, 31**2 **B2.**
4. Upadhyaya, S. K. and P. Andrade. 2004. Development of a soil compaction profile senor. US Patent No. 6,834,550.

HONORS AND AWARDS

Soil Dynamics Award, Tiberias, Israel, 1997
American Society of Agricultural Engineers Certificate of Appreciation, 1995
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PROFESSIONAL AFFIALTION:

1) Member, American Society of Agricultural Engineers (ASAE)
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4) California representative for the NCR-180, Site Specific Crop Management Committee.

RECENT RELEVANT PUBLICATIONS:

Sakai, K., T. Kobayashi, M. Takai, and S. K. Upadhyaya. 1994. Neural network mapping to obtain 2D distributed field information—application to spatially varied infiltration data. Journal Faculty of Agriculture, Hokkaido University 66(1):63-68.

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of soil crust strength. Transactions of the ASAE (American Society of Agricultural Engineers) 38(1):39-44.

Fattah, H. A., and S. K. Upadhyaya. 1996. Effect of soil crust and soil compaction on infiltration in a Yolo loam soil. Transactions of the ASAE (American Society of Agricultural Engineers) 39(1):79-84.

Liu, W., S. K. Upadhyaya, T. Kataoka, and S. Shibusawa. 1996. Development of a texture/soil compaction sensor. Proceedings of the Third International Conference in Precision Agriculture, Minneapolis, MN. pp. 617-630.

Upadhyaya, S. K., J. Jafari Far, S. Shafii, and H. A. Fattah. 1997. Crust-breaking device improves water infiltration into furrows. California Agriculture 51(5):21-23.

S. K. Upadhyaya and N. S. Raghuwanshi. 1999. A semi-empirical equation for cumulative infiltration in furrow irrigations systems. J. Irr.and Drainage Eng. 125(4): 173-178.

Pelletier, M. and Upadhyaya, S. K. 1999. Development of a tomato yield monitor. Computers and Electronics in Agriculture. 23:103-117.

Josiah, M., T. Shikanai, U. A. Rosa, M. Koller. 1999. Mapping infiltration variability in a tomato production system. ASAE Paper No.: 99-1146. ASAE, St. Joseph, MI 49083.

Koller, M., S. K. Upadhyaya, U. A. Rosa, and M. Josiah. 1999. Application of remote sensing in a tomato production system. ASAE Paper No.: 99-1135. ASAE, St. Joseph, MI 49083.

Koller, M., S. K. Upadhyaya, and U. A. Rosa. 2000. Neural network analysis of remote sensing data in crop production. ASAE Paper 001096, ASAE St. Joseph, MI 49085.

Slaughter, D. C., M. G. Pelletier, and S. K. Upadhyaya. 2000. Sensing soil moisture using NIR spectroscopy. Applied Engineering in Agriculture.

Upadhyaya, S. K., W. J. Chancellor, J. V. Perumpral, R. L. Schafer, W. R. Gill, and G. E. VandenBerg (Editors). 2000. Advances in Soil Dynamics, Vol. II. American Society of Agricultural Engineers Monograph, ASAE, St. Joseph, MI 49085. 294 pp.

Upadhyaya, S.K., K. P. Lancas, A. G. Santos-Filho, and N. S. Raghuwanshi. 2001. Evaluation of one-pass tillage equipment versus conventional tillage system. Cal. Ag. 55(5):44-47.

Josaih, M. N., S.K. Upadhyaya, U. Rosa, P. Andrade, and M. Mattson. 2001. Mapping field variability in infiltration rate and evapotranspiration in a tomato production system. ASAE paper Number 011017.

Andrade, P., J. Aguera, S. K. Upadhyaya, B. M. Jenkins, U. A. Rosa, and M. Josiah. 2001. Evaluation of a dielectric based moisture and salinity sensor in-situ applications. ASAE Paper 011010.

Andrade, P., S. K. Upadhyaya, B. Jenkins, and A.G.S. Filho. 2002. Evaluation of UC Davis Compaction Profile Sensor. ASAE Paper. 021185. ASAE, St. Joseph, MI 49085.

Abidine, A, B. Heidman, S. K. Upadhyaya, and S. K. Upadhyaya. 2004. Application of RTK GPS based auto-guidance system in agricultural production. California Agriculture. 58(1):44-47.

Ehsani, M. R., S. K. Upadhyaya, and M. L. Mattson. 2004. Seed location mapping using RTK GPS. Trans. ASAE 47(3):909-914.

Josaih,M, S. K. Upadhyaya, and U. A. Rosa. 2004. The relationship between variability in crop yield and variability in soil physical characteristics. Proceedings of the First International Conference on Emerging Technologies in Agricultural and Food Engineering. P26-32.