Predicting And Preventing Crisis In Irrigated Water Use In A Changing Climate: Measuring, Modeling And Mapping Trends And Changes In Agricultural Water Productivity For California

submitted to Science Program 2010 Solicitation

compiled 2010-02-17 16:57:42 PST

Primary Investigator: Prasad Thenkabail

[page numbers]
Project Information and Executive Summary

Proposal Title: Predicting and Preventing Crisis in Irrigated Water Use in a Changing Climate: Measuring, Modeling and Mapping Trends and Changes in Agricultural Water Productivity for California

Primary Contact Organization: U.S. Geological Survey Western Geographic Science Center

Primary Contact Type: federal agency

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State or Province: AZ

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Telephone: 928-556-7221

E-mail Address: pthenkabail@usgs.gov

Total Amount Requested: $1,884,508

Primary Topic Area: Coupled Hydrologic and Ecosystem Models

Secondary Topic Area(s): Water and Ecosystem Management Decision Support System Development

Descriptive Keywords: agriculture; modeling; remote sensing / imaging; riparian ecology; watershed management

Compliance statement: This project is remote-sensing based, meaning much of the work will involve analyzing imagery. Field data collection will not impact threatened and endangered species or impact other sensitive environmental resources. As a result this project will not require NEPA or CEQA documentation. We intend to request a permit from the San Joaquin River National Wildlife Refuge to conduct work at the Refuge and collect riparian vegetation samples. This request will be made after funding is secured.

Recommend Reviewers

[do we want to require applicants to recommend at least one Reviewer?]
Project Team: Each sub-group has project leads, senior researchers, post-docs, & graduate students: A. Water productivity modeling, mapping and remote sensing • Dr. Prasad S. Thenkabail, PI, (USGS- water productivity mapping, project management) • Dr. Dong Wang, Collaborator, (USDA-ARS, California- crop water productivity mapping, water use) • Post doc 1 (Dr. V. Dheeravath, NAU; water productivity mapping and remote sensing) • Post doc 2 (TBD; NAU; water use\ET modeling, remote sensing) B. Water use (actual ET) modeling • Dr. Pamela Nagler, co-I, (USGS, water use\ET modeling lead, project management) • Post doc 2 (TBD; NAU; water use\ET modeling, remote sensing) • Graduate student (TBD, University of Arizona) Water use\ET modeling and remote sensing C. Hyperspectral remote sensing and Uncertainty analysis in WP mapping • Dr. E. Terrence Slonecker co-I, (USGS, hyperspectral remote sensing, uncertainty analysis) • Post doc 1 (Dr. V. Dheeravath, NAU; water productivity mapping and remote sensing) • Graduate student (TBD, USGS) Remote sensing D. Phenology • Dr. Cynthia Wallace, co-I, (USGS)- (USGS, phenology) • Post doc 1 (Dr. V. Dheeravath, NAU; water productivity mapping and remote sensing) • Graduate student (TBD, University of Arizona) Phenology E. Riparian productivity modeling • Dr. Kristin B. Byrd co-I, (USGS, riparian vegetation, ecological restoration, project management) • Dr. Alex Finkral co-I, (NAU, riparian vegetation, ecological restoration, project management) • Post doc 1 (Dr. V. Dheeravath, NAU; water productivity mapping and remote sensing) • Post doc 2 (TBD; NAU; water use\ET modeling) F. Scenario Analysis for “New Water” and Climate and Water Availability • Dr. Dr. Peter H. Gleick, co-I, (Pacific Institute, Advisor to the project); • Dr. Juliet Christian-Smith, Senior Research Associate, (Pacific Institute, scenario analysis); • Dr. Heather Cooley, Research Associate, (Pacific Institute, scenario analysis); G. End Users\Conservation Leadership • Eric Hopson, end user, (San Joaquin River National Wildlife Refuge, California) • Dr. Dong Wang, end user, (USDA-ARS, California- crop water productivity mapping, water use) • Sub-groups A to E

Executive Summary

Global climate change presents challenges for mitigating and adapting natural resource use and management. In the case of decreased water availability, we propose a new and innovative approach to water productivity (WP, “crop per drop”) mapping using advanced remote sensing data and methods that “pin-point” climate-induced water loss and areas of poor cropland WP. A study conducted in California’s Central Valley irrigated croplands will be ideal for demonstrating the linkages between water, climate, and food that are critically important, both ecologically and economically. Therefore, the central strategy of this action research is to build advanced remote sensing, water-use modeling, and scenario analysis to identify areas of low WP and to quantify the volume of “new water” made available if we increase WP of croplands. This “new water” can then be diverted to environmental and urban uses or simply held as “water bank” for lean years. A complementary goal will be to determine the ecological outcome of increased WP in existing and restored riparian areas. A hydrological-ecological model will relate discharge of agricultural drainage water to riparian productivity and production of plant litter and detritus, a key component of juvenile salmonid food webs. Scenarios of improved irrigated cropland WP will be analyzed spatially, and potential consequences for adjacent riparian areas determined, information decision-makers will need with increasing pressures on water resources.
Contacts and Project Staff

Primary Contact

<table>
<thead>
<tr>
<th>E-Mail</th>
<th><a href="mailto:pthenkabail@usgs.gov">pthenkabail@usgs.gov</a></th>
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<tbody>
<tr>
<td>Last Name</td>
<td>Thenkabail</td>
</tr>
<tr>
<td>First Name</td>
<td>Prasad</td>
</tr>
<tr>
<td>Organization</td>
<td>U.S. Geological Survey Western Geographic Science Center</td>
</tr>
<tr>
<td>Work Telephone</td>
<td>928-556-7221</td>
</tr>
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Primary Investigator

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<th><a href="mailto:pthenkabail@usgs.gov">pthenkabail@usgs.gov</a></th>
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Qualifications: See Appendix for complete CV of this Participant.

Participant #2

<table>
<thead>
<tr>
<th>Salutation</th>
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<tbody>
<tr>
<td>Last Name</td>
<td>Nagler</td>
</tr>
<tr>
<td>First Name</td>
<td>Pamela</td>
</tr>
<tr>
<td>Title</td>
<td>Research Geographer (ET modeling/crop water use)</td>
</tr>
<tr>
<td>Organization</td>
<td>U.S. Geological Survey</td>
</tr>
<tr>
<td>Position</td>
<td>Co-PI</td>
</tr>
<tr>
<td>Responsibilities</td>
<td>Evapotranspiration modeling, irrigated agriculture and riparian water use determination (through ET modeling), Uncertainty analysis in water use assessment.</td>
</tr>
<tr>
<td>E-mail</td>
<td><a href="mailto:pnagler@usgs.gov">pnagler@usgs.gov</a></td>
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Qualifications: See Appendix for complete CV of this Participant.

Participant #3

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<td>Last Name</td>
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<tr>
<td>First Name</td>
<td>Kristin</td>
</tr>
<tr>
<td>Title</td>
<td>Physical Scientist</td>
</tr>
<tr>
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<td>U.S. Geological Survey</td>
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<td>Responsibilities</td>
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</tr>
<tr>
<td>E-mail</td>
<td><a href="mailto:kbyrd@usgs.gov">kbyrd@usgs.gov</a></td>
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Participant #4

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</table>
Last Name    Finkral
First Name    Alex
Title         Assistant Professor
Organization  Northern Arizona University
Position      Co-PI
Responsibilities  Ecological modeling, ecological restoration
E-mail        alex.finkral@nau.edu
Qualifications  See Appendix for complete CV of this Participant.

Participant #5

Salutation  Dr.
Last Name    Gleick
First Name   Peter
Title        President
Organization  Pacific Institute
Position     Subcontractor
Responsibilities  Project advice, scenario analysis
E-mail       pgleick@pipeline.com
Qualifications  See Appendix for complete CV of this Participant.

Participant #6

Salutation  Dr.
Last Name    Dong
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Position     Subcontractor
Responsibilities  Crop productivity modeling, water use modeling, water productivity mapping.
Collaborator. End User.
E-mail       dong.wang@ars.usda.gov
Qualifications  See Appendix for complete CV of this Participant.

Participant #7

Salutation  Dr.
Last Name    Wallace
First Name   Cynthia
Title        Research Geographer
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Position     Co-PI
Responsibilities  Phenology mapping and water use assessments based on phenology
E-mail       cwallace@usgs.gov
Qualifications  See Appendix for complete CV of this Participant.
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<td><strong>Last Name</strong></td>
<td>CHRISTIAN-SMITH</td>
</tr>
<tr>
<td><strong>First Name</strong></td>
<td>Juliet</td>
</tr>
<tr>
<td><strong>Title</strong></td>
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</tr>
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<td><strong>Organization</strong></td>
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<td><strong>Responsibilities</strong></td>
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<tr>
<td><strong>E-mail</strong></td>
<td><a href="mailto:juliet@pacinst.org">juliet@pacinst.org</a></td>
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<tr>
<td><strong>Last Name</strong></td>
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<tr>
<td><strong>First Name</strong></td>
<td>Heather</td>
</tr>
<tr>
<td><strong>Title</strong></td>
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</tr>
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<tr>
<td><strong>First Name</strong></td>
<td>Terrance</td>
</tr>
<tr>
<td><strong>Title</strong></td>
<td>Research Geographer</td>
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<td><strong>Position</strong></td>
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<tr>
<td><strong>Responsibilities</strong></td>
<td>Advanced remote sensing analysis, mapping at different resolutions or scales</td>
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<tr>
<td><strong>E-mail</strong></td>
<td><a href="mailto:tslonecker@usgs.gov">tslonecker@usgs.gov</a></td>
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<td><strong>Qualifications</strong></td>
<td>See Appendix for complete CV of this Participant.</td>
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<tr>
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<tr>
<td><strong>First Name</strong></td>
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</tr>
<tr>
<td><strong>Title</strong></td>
<td>Post doctoral fellow (water productivity)</td>
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<tr>
<td><strong>Organization</strong></td>
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<td><strong>Position</strong></td>
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<tr>
<td><strong>Responsibilities</strong></td>
<td>Water productivity modeling and mapping, remote sensing data analysis, algorithm development, heavy computing</td>
</tr>
<tr>
<td><strong>E-mail</strong></td>
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</tr>
</tbody>
</table>
The candidate will have following skills: 1. highly skilled in remote sensing theory and software; 2. excellent knowledge of remote sensing data; 3. programing skills; 4. water productivity model development; 5. irrigated croplands and water use.

Participant #12

Salutation Dr.
Last Name TBD
First Name TBD
Title water use modeler
Organization U.S. Geological Survey and Northern Arizona University
Position Subcontractor
Responsibilities Water use (ET) modeling, algorithm development, remote sensing data analysis, spatial model development.
E-mail

The candidate will have following skills: 1. highly skilled in remote sensing theory and software; 2. excellent knowledge of remote sensing data; 3. programing skills; 4. top skills in water use modeling (surface energy balance models and VI based models); 5. irrigated croplands and water use.
Conflict of Interest

Primary Investigator
Prasad Thenkabail

Co-PI(s)

Supporting Staff
[untested]

Subcontractor

Individuals who helped with proposal development

<table>
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<th>Last Name</th>
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<tr>
<td>Hopson</td>
<td>Eric</td>
<td>San Joaquin River National Wildlife Refuge, California</td>
<td>End User\Conservation leadership; San Joaquin River National</td>
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[refactored ...]
# Task and Budget Summary

[Is it truly better to center numbers in columns, rather than right-justify them? or align '.' in dollar figure?]

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<td>Dr. Pamela Nagler; Dr. Kristin Byrd; Dr. Alex Finkral; Dr. Peter Gleick; Dr. Wong Dong; Dr. Cynthia Wallace; Dr. Juliet CHRISTIAN-SMITH; Ms. Heather Cooley; Dr. Terrance Slonecker; Dr. TBD TBD; Dr. TBD TBD</td>
<td>Project initiation meeting</td>
<td>$14,000</td>
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<td>2</td>
<td>Field data collection</td>
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<td>Dr. Pamela Nagler; Dr. Kristin Byrd; Dr. Alex Finkral; Dr. Wong Dong; Dr. Cynthia Wallace; Dr. Terrance Slonecker; Dr. TBD TBD; Dr. TBD TBD</td>
<td>Crop Data: For the purpose of crop and water productivity mapping, extensive sets of crop biophysical and yield data will be gathered from 30-50 sample locations for each crop every 15-20 days over two growing seasons. These sample locations will be selected randomly from within the 10 km×10 km representative areas (Figure 1). The field campaign will be conducted at times that correspond with satellite (e.g. Landsat, GeoEye-1, IKONOS, Quickbird, RadipEye and EO-1) overpass dates over the study areas. Photosynthetically active radiation (PAR) and leaf area index (LAI) (m2/m2) will be measured through an AccuPAR LP-80 ceptometer, as well as narrowband spectral reflectance measurements with an Analytical Spectral DevicesTM (ASD) spectroradiometer. These will be carried out along 30 m transects. For crops, plots of 10 m2 will be harvested: the wet and dry biomass (kg) will be measured by weighing - on site (green) and in the lab (oven 70 °C), respectively. Plant conditions, (e.g. height, growth stage, cover fraction) will be recorded and digital photographs taken. Riparian Data: Similar measurements will be taken at the same frequency and duration on cottonwood and dominant willow species within each 10 km×10 km representative</td>
<td>$118,058</td>
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area, and will also correspond with satellite overpass dates. Narrowband spectral reflectance, LAI, tree height, and diameter at breast height (1.3 m) measurements will be taken. Core samples at breast height and representative 1 m² biomass samples will also be collected to characterize plant biomass size and age. Litter traps will be installed to collect and measure tree litter production at monthly time intervals (Reid et al. 2008, Gawne et al. 2007). See section 4.0 and its sub-sections for various data collected.

### Data acquisition and processing

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<td>Dr. Pamela Nagler; Dr. Kristin Byrd; Dr. Alex Finkral; Dr. Cynthia Wallace; Dr. Terrance Slonecker; Dr. TBD TBD; Dr. TBD TBD</td>
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</table>

We will acquire satellite sensor data across spatial, spectral, radiometric, and temporal resolutions. These data are categorized as (Table 1): A. hyperspectral, B. hyperspatial, and C. advanced multispectral. Advanced multispectral Landsat ETM+ data will be acquired for the entire Central Valley. Hyperspectral (e.g., Hyperion, spectroradiometer-see letter of support for the later) and hyperspatial imagery (GEOEYE\Quickbird\IKONOS) will be acquired for the entire representative 10 km×10 km blocks of the five major crops (see Figure 4). These images will help establish exact crop areas of the five target crops (rice, corn, wheat, alfalfa and cotton; Figure 4) as well as other irrigated areas and riparian vegetation cover. We (USGS) has free access to the entire archive of commercial high resolution imagery (Quickbird, IKONOS, Geoeye-1) through two US government sources: (a) Commercial Imagery Derived Requirement (CIDR) Database of USGS, and (b) National Geospatial Intelligence Agency (https://warp.nga.mil/). Second, the entire archive of EO-1 Hyperion and ALI imagery became web-enabled (free) on July 1, 2009. Third, we will use ASD spectroradiometer (400-2500 nm) available from the USGS to gather hyperspectral data of regrowth of vegetation. Fourth, a wall-to-wall coverage of web-enabled Landsat data is available for all. Other data acquired include: Secondary data Meteorological data Water withdrawal and delivery data
Isotope samples of riparian vegetation, crop/riparian biophysical and yield data as well as spectroradiometer data. Riparian Data. These are described in detail in section 4.0 and its sub-sections. Data harmonization and standardization is one of the first steps to ensure high quality of data and the products generated from them. Satellite sensor data will be normalized to at-sensor reflectance and to surface reflectance. Other data such as Secondary data, Meteorological data, Water withdrawal and delivery data.

Delineating crop types or riparian vegetation categories is an important first step to ensure precise water use estimates from these land use classes. Detailed, high resolution crop and vegetation maps will be generated for the five 10 km×10 km representative areas. This aspect of the research will fuse Landsat ETM+, IKONOS, and Hyperion imagery, through Spectral-textural-temporal algorithms, which offer three advantages: (1) a data record of crop and riparian vegetation signatures (Hyperion), (2) high-resolution images for the textural characterization of crops and riparian vegetation (IKONOS), and (3) a wall-to-wall coverage along with a record of multi-spectral and multi-temporal phenology of irrigated areas (Landsat) and riparian vegetation (this we will do by extrapolating the understanding developed through models developed in 10 km×10 km representative areas). Detailed description in section 5.1, section 5.1.1, and in Figure 5.

Currently, in California, WU (actual ET) is commonly estimated from reference ET, calculated from weather station data, and estimated crop coefficients (Allen et al., 2007) available from the California Irrigation Management Information System (CIMIS), which includes a network of over 120 weather stations.

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<td>4</td>
<td>crop type and riparian vegetation mapping</td>
<td>Dr. Pamela Nagler; Dr. Kristin Byrd; Dr. Alex Finkral; Dr. Cynthia Wallace; Dr. Terrance Slonecker; Dr. TBD TBD; Dr. TBD TBD</td>
</tr>
<tr>
<td>5</td>
<td>ET (water use) modeling and mapping</td>
<td>Dr. Pamela Nagler; Dr. Kristin Byrd; Dr. Cynthia Wallace; Dr. TBD TBD; Dr. TBD TBD</td>
</tr>
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</table>

$265,000

$395,000
Because crop coefficients vary with crop growth rate, planting density, and management practices, they do not return actual crops’ WU (Trout & Johnson, 2007, Cooley et al., 2009). As a result, crop over-irrigation or under-irrigation occurs as a result of lack of spatial knowledge of water use and related water productivity (WP). This can be improved by use of remote sensing, which is capable to detect the spatial and temporal distribution of WU within and among crops by gathering information mostly on solar radiation, surface temperature, and emissivity. In this proposal actual ET (water use) of crops and riparian vegetation will be done using 2 modeling approaches: 1. Surface energy balance models using thermal data 2. Vegetation-index (VI) based models Section 5.0 and its sub-section describe these modeling process in detail.

Two alternative approaches to modeling productivity will be tested (Figure 5): (1) establishing an empirical relationship between spectral reflectance and biomass (statistical approach); and (2) defining a theoretical model that describes reflectance as a function of several bio-physical parameters (physically-based models). The statistical approach will relate different wavebands to either popular vegetation indices (e.g., normalized difference vegetation indices (NDVIs), transformed vegetation indices (TVIs), soil adjusted vegetation indices (SAVI), crop moisture sensitive indices (CMSIs)) or advanced hyperspectral vegetation indices (HVIs) to establish crop and riparian biophysical and yield characteristics. The physically-based approach will compare two models: (A) the Scattering by Arbitrary Inclined Leaves model (SAIL) coupled with the radiative transfer model PROSPECT (Jacquemoud et al., 2009) or variations of it (e.g. PROSAIL; Jacquemoud et al., 2009), combined with a Look-Up Table approach for solving the inverse problem; and (B) the Surface Energy Balance Algorithm for Land (SEBAL) biomass growth routine that uses light-use
efficiency and photosynthetically active radiation models. Further details in section 5.1.2 and Figure 5.

We will develop algorithms based on spectral matching techniques (SMTs) to derive phenol-metrics of croplands and riparian vegetation using time-series satellite sensor data (Thenkabail et al., 2007). The methods will include quantitative SMTs such as: (a) spectral correlation similarity, and (b) spectral similarity value. Several studies use time-series satellite sensor data to extract pheno-metrics, such as onset of greenness and time of maximum greenness, which describe the pattern of greenness at that location throughout the year (e.g., Figure 3). These pheno-metrics will then be used in water use models (Section 5.2).

Analysis of the historical phenology of the various crops, adjacent natural landscapes and associated riparian areas will inform whether and how the dynamics of these various vegetated landscapes are linked. The phenology of natural vegetation adjacent to croplands will capture information about ambient environmental conditions for the locale, including the impact of amount and timing of precipitation. Comparing the phenology of croplands and adjacent natural landscapes on a yearly basis will reveal how well-coupled irrigation intensity is to the observed ambient environmental conditions and whether irrigation intensity is directly related to the vigor of riparian vegetation.

Characterizing the linkages between the dynamics of the various vegetated landscapes will help calibrate and refine management actions related to active irrigation. Section 5.3 describes this in detail.

Water productivity (WP) maps will be produced for the five major irrigated crops as well as riparian vegetation which will “pin point” areas of high and low WP. The area under various levels of low WP will be established and the water savings scenarios when the low WP areas are converted to various higher WP levels will be determined and highlighted. WP
Uncertainty in Crop and water productivity models and maps 20 32 Dr. Pamela Nagler; Dr. Kristin Byrd; Dr. Terrance Slonecker; Dr. TBD TBD; Dr. TBD TBD

A complete error analysis and validation is necessary in order to make effective use of the water productivity maps created in this project. The different models will be evaluated to see which produces the best results by examining descriptive statistics computed from the error matrix, such as overall, producer’s, and user’s accuracies (Congalton and Green, 2009; Figure 7). Since the models and maps are produced using hyperspectral, hyperspatial, and advanced multispectral data of wide array of resolutions and error and accuracy assessment will help us determine how uncertainties propagate across resolutions, radiometry, and band width.

$56,000

Linkages between agricultural and riparian water use will be coupled with riparian biomass and litter production estimates to create a hydrological-ecological model of riparian productivity. Through monthly data collection, this model will establish the intra-annual connection between water availability and riparian carbon exports to the salmonid food web via litter production and dispersion. It will also establish for specific areas riparian carbon export dependencies on agricultural water sources. Figure 6 demonstrates how data products generated in this study will be applied in the development of this model. Within the San Joaquin NWR, monthly estimates of riparian biomass and litter production for Fremont cottonwood and willow species by age class combined with analysis of carbon content of litter production will be used to estimate monthly estimates of carbon inputs for a given stream reach. Phenology studies will inform how biomass production varies with temperature and precipitation. Isotope analysis will determine sources of water used by plants, water use efficiency, and the fraction of ET attributed to evaporation and transpiration. Combined with riparian water use maps, the isotope
analysis will determine what portion of water used is from agricultural sources. A dynamic measure of riparian water productivity will be calculated as a ratio of plant biomass or litter production (g/m²) to water use (m³/m²). We will investigate connectivity between agricultural and riparian water use through isotope sampling and build a hydro-eco model that relates riparian water use to primary productivity and litter production of dominant Central Valley riparian plants, a significant component of salmonid food webs. Focusing on the San Joaquin River National Wildlife Refuge, we will demonstrate the ecological consequences and restoration opportunities that increased crop water productivity generates for riparian vegetation, identify where ecosystems may be impacted by reduced return flows, and demonstrate how these ecosystems could be supported with an additional water supply from agricultural return flow savings (possibly up to 30% more water). We will show through improved WP in irrigated croplands, various quanta of “new water” that becomes available for alternative uses like riparian restoration, re-forestation, recreation, and health. Through a partnership with the Refuge, our models can be used to explore the application of riparian water use maps for future riparian restoration planning in the Central Valley, especially under different climate change scenarios. Detailed descriptions is section 5.6 and 5.7

A set of scenarios provides a broad look at how the future may evolve in response to (1) forces largely outside the control of policy makers, and (2) policy choices designed to shape future conditions. Such a “scenario analysis” approach can help resource managers and interested stakeholders better understand the inherent uncertainties about future management and, in turn, help reveal more innovative and successful management strategies for adapting to possible futures. Ultimately, the point—and power—of scenarios is not to
develop a precise view or prediction of the future. It is to enable us to look at the present in a new and different way, and to find new possibilities and choices we might have previously overlooked or ignored. Once WP maps are produced at different resolutions for the representative areas and extrapolated to Central Valley using the best models, we will build spatial models in ArcGIS 9.3 that will simulate “new water” saved through various scenarios (Byrd, 2009; Kooistra et al., 2008, Carpenter et al., 2005) such as: (a) improved WP and (b) re-allocation of crops (e.g., growing wheat instead of rice). The output of these models will provide visualization of where, when, and how much water is saved. In the representative 10 km x 10 km study areas where riparian primary productivity and riparian water sources are established, we will demonstrate the ecological consequences and restoration opportunities that increased crop water productivity generates for riparian vegetation, identify where ecosystems may be impacted by reduced return flows, and demonstrate how these ecosystems could be supported with an additional water supply from agricultural return flow savings (possibly up to 30% more water). Maps of scenario outputs will be made publicly accessible via a USGS website that will contain a Web Mapping Service generated with ArcGIS Server 9.3. Users will be able to view and query, compare and contrast scenario maps, and generate customized maps from the website (e.g.,: http://landcovertrends.usgs.gov). Section 7.0 and section 8.0 provide detailed description on scenario analysis showing where and how water is saved and by how much. The scenario analysis will also show the water availability and water use by crops in a changing climate based on downscaled climate models. development of scenarios of future water use on agricultural lands based on the water productivity maps developed by other research team members. The scenario outcomes would identify spatially where we could gain "new water" and the
opportunities for restoration. The research will analyze potential reductions in applied water, which allow farmers and water agencies to remove less water from streams, improving stream quality and ecosystem health, while reducing pumping, delivery, and treatment costs. Scenarios would spatially explicit changes in climatic factors, crop choices, irrigation technologies, irrigation management practices, and crop cultivation practices.

The models and maps on crop productivity, crop water use (ET), water productivity, and various scenario analysis will all be made available through USGS web portal dedicated to the project. One of the key goals will be to see how well the end users apply the research findings in their research. Based on these applications, the value and impact of research will be assessed. In the last 3 months we propose to hold one workshop inviting the state and national water and water related agencies.

Dissemination and workshops

Dr. Pamela Nagler; Dr. Kristin Byrd; Dr. Alex Finkral; Dr. Peter Gleick; Dr. Wong Dong; Dr. Cynthia Wallace; Dr. Juliet CHRISTIAN-SMITH; Ms. Heather Cooley; Dr. Terrance Slonecker; Dr. TBD TBD; Dr. TBD TBD

$17,000
# Schedule of Deliverables

<table>
<thead>
<tr>
<th>Additional deliverables</th>
<th>Description</th>
<th>Start Month</th>
<th>End Month</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crop and riparian mapping, crop productivity models and maps</td>
<td>Multi-resolution crop and vegetation maps and models</td>
<td>1</td>
<td>32</td>
</tr>
<tr>
<td>ET (water use) models and maps of crops and riparian</td>
<td>Thermal and non-thermal ET models</td>
<td>8</td>
<td>32</td>
</tr>
<tr>
<td>Water productivity (WP) models and maps</td>
<td>Establish areas of low and high WP scenario models, visualization, uncertainty analysis</td>
<td>12</td>
<td>33</td>
</tr>
<tr>
<td>Scenario analysis, uncertainties and errors</td>
<td>Web portals, workshops, presentations, end user application</td>
<td>1</td>
<td>32</td>
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<tr>
<td>Dissemination</td>
<td></td>
<td>24</td>
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## 12.1 U.S. Geological Survey (USGS)

<table>
<thead>
<tr>
<th>Rates</th>
<th>Time</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
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<tr>
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<td><strong>Subtotal Other</strong></td>
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<td><strong>Subtotal Indirect costs</strong></td>
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<td><strong>Subtotal</strong></td>
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<td><strong>Fringe benefits</strong></td>
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<td><strong>Subtotal Fringe Benefits</strong></td>
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<td><strong>TOTAL USGS direct costs</strong></td>
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### 12.1.1 Salaries & Wages - Staff & Faculty

- **Senior Researcher**: Dr. Heather Cooley (Senior Research Associate; Scenario Analysis) $62,500 per yr 14% $8,750 $9,188 $9,647 $27,584
- **Senior Researcher**: Dr. Juliet Christian-Smith (Senior Research Associate; Scenario Analysis) $60,000 per yr 14% $8,400 $8,820 $9,261 $26,481
- **Co-I**: Dr. Peter Gleick (Advisor to the project, Scenario analysis) $138,800 per yr 6% $8,328 $8,744 $9,162 $26,234

### 12.1.2 Salaries & Wages - Staff & Faculty - Consultants

- **Graduate student**: to be identified (to work with Cynthia) $25,000 per yr 50% $12,500 $13,125 $13,781 $39,406
- **Graduate student**: to be identified (to work with Terrence) $25,000 per yr 50% $12,500 $13,125 $13,781 $39,406

### 12.1.3 Salaries & Wages - Staff & Faculty - Consultants

- **PI**: Dr. Prasad S. Thenkabail, USGS, WGSC: water productivity modeling and mapping, advanced remote sensing $121,000 per yr 25% $30,250 $31,760 $33,351 $95,363

### 12.1.4 Field work, Data collection and synthesis, Travel

- **Post doc (crop productivity mapping, remote sensing)**: Dr. Venkat Dheeravath (to work with Prasad), based at USGS Flagstaff $55,000 per yr 100% $55,000 $57,750 $60,638 $173,388

### 12.1.5 Other

- **Senior Researcher**: Dr. Wang Dong, United States Department of Agriculture (USDA), ARS, California $3,500 per yr $3,675 $3,859 $11,034

### 12.1.6 Data Acquisition and Equipment

- **Satellite sensor data acquisition** $5,200
- **Computer for post-docs**: $29,200
- **Data disk storage (20 TB RAID) and server** $14,400

### 12.1.7 F&A/Indirect costs USGS (estimated rate)

- **Fringe benefits (FDN full-time employees)** @ 6.00% $33,956 $34,993 $36,077 $105,026

### 12.2 Northern Arizona University (NAU)

- **Graduate student**: to be identified $21% $1,838 $1,929 $2,026 $5,793
- **Graduate student**: to be identified $21% $1,764 $1,852 $1,945 $5,561
- **Graduate student**: to be identified $35% $19,250 $20,213 $21,223 $60,686
- **Senior Researcher**: Dr. Wang Dong, United States Department of Agriculture (USDA), ARS, California $3,500 $3,675 $3,859 $11,034

### 12.3 The Pacific Institute for Studies in Development, Environment, and Security

- **PI**: Dr. Peter Gleick (Advisor to the project, Scenario analysis) $138,800 per yr 6% $8,328 $8,744 $9,162 $26,234

### 12.4 Proposal Title

- **Title**: Predicting and preventing crisis in irrigated water use in a changing climate: measuring, modeling, and mapping trends and changes in agricultural water

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**Proposal by: U.S. Geological Survey (USGS)**

**Sponsor: CALFED Science Program. 2009 PSP**

**Proposal Title:** Predicting and preventing crisis in irrigated water use in a changing climate: measuring, modeling, and mapping trends and changes in agricultural water
Budget Justification

Predicting and Preventing Crisis in Irrigated Water Use in a Changing Climate: 
Measuring, Modeling and Mapping Trends and Changes in Agricultural Water Productivity for California

12.0 Budget Justification

A total budget of $1,884,508 is requested for three years: $643,551 during year 1, $624,184 during year 2, $616,773 during year 3. Of this USGS requests $373,232 during year 1, $366,287 during year 2, $355,692 during year 3, for a total of $1,095,211. Northern Arizona University requests $228,364 during year 1, $213,844 during year 2, $214,824 during year 3, for a total of $657,032. The Pacific Institute for Studies in Development, Environment, and Security requests are: $41,956 during year 1, $44,053 during year 2, $46,256 during year 3, for a total of $132,265.

The budget is spread across 2 institutions to achieve the following specific goals:

A. U.S. Geological Survey (USGS): USGS will lead the overall project coordination, several major components of the project (listed below), and will be responsible for the timely deliverables. The major project components that USGS will lead will be:
   - Crop productivity modeling and mapping
     Conceptualization, modeling, mapping, and validation
   - Evapotranspiration (ET) modeling (water use) and mapping
     Conceptualization, modeling, mapping, and validation
   - Water productivity (WP) modeling and mapping
     Conceptualization, modeling, mapping, and validation
     Pinpointing areas of low and high WP in irrigated areas
     Developing scenarios for water savings and creating visualization tools of water savings in different scenarios
   - Riparian productivity modeling and restoration planning

B. Northern Arizona University (NAU): NAU will host 2 post docs and an ecologist with expertise in water productivity mapping and plant water use (ET modeling). In addition, these scientists will work with the entire team in processing remote sensing data, building water use, crop productivity, and water productivity models, and providing expert knowledge on ecological inputs for various models. The NAU team is located close to the principal investigator (PI) at the USGS in Flagstaff and the post docs will work under the close guidance of Drs. Thenkabail and Finkral. The post docs will also receive regular input and advice from other USGS team members (Drs. Nagler, Byrd, Slonecker, and Wallace). The specific leadership for NAU will be:
   - Crop productivity modeling and mapping
     Field data gathering, image data normalization
     Building crop productivity models and maps for 5 major crops
Validation of crop productivity models and maps at various resolutions (taking hyperspectral, hyperspatial, and advanced multi-spectral data)

- ET modeling (water use) and mapping
  - ET modeling (water use) for agricultural crops and riparian vegetation
  - Building a comprehensive meteorological and remote sensing database for ET modeling
  - Validation of ET models and maps at various resolutions (using hyperspectral, hyperspatial, and advanced multi-spectral data)

- Water productivity modeling and mapping
  - Develop water productivity models and maps
  - Pinpoint areas of low and high water productivity
  - Establish uncertainties and errors in water productivity (using hyperspectral, hyperspatial, and advanced multi-spectral data)

- Scenario analysis of water availability
  - Develop scenarios of water availability based on improved water productivity of agricultural croplands

12.1 Salaries of Staff (budget sub-sections: 12.1.1, 12.2.1, 12.31.1) from sub-groups listed below

The budget is carefully planned to achieve goals systematically. The approach is to form sub-groups that are responsible for specific components of the work and then link with other groups to ensure that project goals and deliverables are achieved on time.

The sub-groups are formed to: (a) provide efficiency, (b) ensure focus on goals, and (c) achieve goals in a timely manner. Each sub-group has project leads, senior researchers contributing to sub-group goals, and solid computing support from post-docs & grad students. Overall, the set-up allows close and constant interactions and intellectual discussions to advance science objectives of the project.

The functioning of the sub-groups, their responsibilities, and how they inter-link with other subgroups is outlined below:

**Sub-group A: Water productivity modeling, mapping and remote sensing**

- Dr. Prasad S. Thenkabail (USGS), PI
- Dr. Wang Dong (USDA-ARS), Collaborator
- Dr. Dheeravath (water productivity mapping, remote sensing data processing, crop productivity mapping, crop type mapping)
- TBD, Post-doc 2 (ET\water use modeling)

Dr. Prasad Thenkabail (Prasad) has extensive experience in water productivity mapping, water use assessments, cropland mapping, and crop productivity mapping. He has 20+ years of experience handling a wide array of remote sensing data. He recently led the IWMI’s global irrigated area mapping effort and edited a recent book on the subject entitled: “Remote Sensing of Global Croplands for Food Security”. Prasad will provide intellectual leadership in remote sensing data analysis, crop productivity mapping, water use modeling, and water productivity modeling and mapping. He also will be involved closely in uncertainty analysis and to determine
how pixel resolution, radiometry, and band width differences cause differences in water productivity analysis.

Dr. Wang Dong is a research leader and a soil scientist with the USDA-ARS water management research. He has nearly 20 years of crop and water productivity modeling and crop water use modeling. His extensive knowledge in California Agriculture and advice on the same for the project will be invaluable. Dr. Wang will play a key role in the use of crop productivity, water productivity, and water use models and maps developed in this research in California’s agriculture.

The post docs will have complementary skills: **one post doc** (Dr. Dheeravath) with very strong skills in multi-resolution remote sensing data normalization, processing, and building models of crop productivity. The **second post doc**, will be a water use (ET) expert- who has extensive ET algorithm experience including SEBAL, METRIC, SETI, and non-thermal data based algorithm (Nagler et al., 2005, 2009).

The post docs will prepare base normalized hyperspectral, hyperspatial, and advanced multi-spectral data required by all sub-groups. They will also ensure standardized: (a) field-plot data on crop biophysical and yield, (b) meteorological data from network of climate stations, (c) water delivery data from the California Department of Water Resources, (d) spectroradiometer data of agricultural crops, and (e) flux tower data from sentillometers, sap flow meters, and lysimeters. They will organize the data for model building and validation and make these standardized data available for the entire team (sub-groups B to G).

**Salaries and Wages of Staff for Sub-group A**

*Name:* Dr. Prasad S. Thenkabail  
*Title:* Research geographer-14 (Responsibilities: PI, project management, water productivity modeling and mapping, crop productivity modeling and mapping, water use modeling and mapping, remote sensing, deliverables)  
*Organization:* U.S. Geological Survey  
*Proposed efforts Year 1:* 3.0 person-months (0.25 FTE)  
*Proposed efforts Year 2:* 3.0 person-months (0.25 FTE)  
*Proposed efforts Year 3:* 3.0 person-months (0.25 FTE)

*Name:* Dr. Wang Dong  
*Title:* Research Leader and Soil Scientist (Responsibilities: Collaborator, crop-water productivity modeling advice, crop water use modeling advice, use of crop and water productivity models in California’s agriculture)  
*Organization:* USDA-ARS  
*Proposed efforts Year 1:* un-paid collaborator  
*Proposed efforts Year 2:* un-paid collaborator  
*Proposed efforts Year 3:* un-paid collaborator

Dr. Wang Dong will travel to project meetings to advise post docs on the crop and water use model development strategies. He will play a key role in use of the models developed and maps produced in the project in California’s agriculture. He will evaluate the models and maps and
suggest any improvements needed. A travel budget of $3500 for year 1, $3675 for year 2, and $3859 for year 3 is provided.

Name: Post doc 1 (water productivity modeling and mapping, remote sensing, data processing, heavy computing)
Title: Post-doc 1
Organization: Northern Arizona University (NAU)
Proposed efforts Year 1: 12.0 person-months (1.0 FTE)
Proposed efforts Year 2: 12.0 person-months (1.0 FTE)
Proposed efforts Year 3: 12.0 person-months (1.0 FTE)

Name: Post doc 2 (ET\water use modeling, remote sensing)
Title: Post-doc 2
Organization: Northern Arizona University (NAU)
Proposed efforts Year 1: 12.0 person-months (1.0 FTE)
Proposed efforts Year 2: 12.0 person-months (1.0 FTE)
Proposed efforts Year 3: 12.0 person-months (1.0 FTE)

Sub-group B: Water use (actual ET) modeling
- Dr. Pamela Nagler (USGS-BRD) Lead co-I
- Graduate student (TBD, University of Arizona) Water use\ET modeling and remote sensing
- TBD, Post-doc 2 (ET\water use modeling) - same as in sub-section A

Dr. Pamela Nagler (Pamela) is an expert in ET (water use) modeling. Her ET work is widely published (see her CV) and her ET algorithms are used to compute crop water use as well as riparian water use. Pamela will lead the ET modeling (water use) and mapping effort. She will advance the use of her recent algorithms by mapping ET at various resolutions (4 m to 1 km). The models and maps will be thoroughly evaluated by uncertainties and errors by comparing remote sensing derived ET with flux towers, lysimeter measurements, and sap flow measurements.

Pamela will hire a graduate student from the University of Arizona (UoA) to help her with ET modeling work. The graduate student will work 50% of time on the project and will specifically focus on: (a) running various ET algorithms, (b) modifying algorithms for specific conditions, (c) comparing VI-based ET models SEBAL, METRIC, and SETI, and (d) performing uncertainty analysis.

One of the post docs (ET modeler) based at Northern Arizona University (Flagstaff) will also be jointly guided by Pamela (along with Prasad). The NAU ET post doc will process all satellite imagery and make them available to Pamela and her graduate student. The ET modeling team (Pamela, post doc, graduate student, Prasad) will use a wide array of standardized: (a) field-plot data on crop biophysical and yield, (b) meteorological data from network of climate stations, (c) water delivery data from the California Department of Water Resources, (d) spectroradiometer
data of agricultural crops, and (e) flux tower data from sentillometers, sap flow meters, and lysimeters. They will work closely with sub-groups A, C, and D.

**Salaries and Wages of Staff for Sub-group B**

**Name:** Dr. Pamela Nagler  
**Title:** Research geographer (Responsibilities: ET\water use modeling for agricultural croplands and riparian systems, comparison of results with SEBAL, METRIC, and SETI. Uncertainty analysis)  
**Organization:** U.S. Geological Survey  
**Proposed efforts Year 1:** 2.4 person-months (0.20 FTE)  
**Proposed efforts Year 2:** 2.4 person-months (0.20 FTE)  
**Proposed efforts Year 3:** 2.4 person-months (0.20 FTE)

**Name:** graduate student (ET modeling, algorithm development and validation)  
**Title:** Graduate student  
**Organization:** University of Arizona (UoA)  
**Proposed efforts Year 1:** 6.0 person-months (0.5 FTE)  
**Proposed efforts Year 2:** 6.0 person-months (0.5 FTE)  
**Proposed efforts Year 3:** 6.0 person-months (0.5 FTE)

**Name:** Post doc 2 (ET\water use modeling, remote sensing)- same as in sub-section A  
**Title:** Post-doc 2  
**Organization:** Northern Arizona University (NAU)  
**Proposed efforts Year 1:** 12.0 person-months (1.0 FTE)  
**Proposed efforts Year 2:** 12.0 person-months (1.0 FTE)  
**Proposed efforts Year 3:** 12.0 person-months (1.0 FTE)

**Sub-group C: Hyperspectral remote sensing and Uncertainty analysis in WP mapping**

- Dr. E. Terrence Slonecker (USGS)- **Lead co-I**  
- Graduate student (TBD, USGS) Remote sensing

Dr. Terrence Slonecker (Terry) is an expert in multi-resolution remote sensing techniques and methods. He has published extensively in hyperpectral remote sensing, vegetation indices, and applications of remote sensing for many terrestrial applications. Terry will play a key role in remote sensing data analysis. Specifically, in : (a) crop productivity modeling and mapping, (b) hyperspectral data analysis, and (c) establishing uncertainties and errors in modeling efforts. Terry will work closely with sub-group A and will provide insights and advice to the 2 post docs based at NAU.

A graduate student in multi-temporal satellite sensor data analysis will work 50% of her/his time developing models on crop productivity using hyperspectral, hyperspatial, and advanced multispectral data. The models and indices developed through this effort will be in close coordination with the NAU post doc on water productivity and the PI (Dr. Thenkabail) will also advise from time to time.
Salaries and Wages of Staff for Sub-group C

Name: Dr. Terrence Slonecker
Title: Research Geographer (Responsibilities: crop productivity modeling and mapping using multi resolution remote sensing, hyperspectral remote sensing data analysis, uncertainty analysis in crop productivity models and maps)
Organization: U.S. Geological Survey
Proposed efforts Year 1: 1.0 person-months (0.08 FTE)
Proposed efforts Year 2: 1.0 person-months (0.08 FTE)
Proposed efforts Year 3: 1.0 person-months (0.08 FTE)

Name: TBD (multi resolution remote sensing data processing, crop productivity models)
Title: graduate student
Organization: U.S. Geological Survey
Proposed efforts Year 1: 6.0 person-months (0.5 FTE)
Proposed efforts Year 2: 6.0 person-months (0.5 FTE)
Proposed efforts Year 3: 6.0 person-months (0.5 FTE)

Sub-group D: Riparian productivity modeling
- Dr. Kristin B. Byrd (USGS)- Lead co-I
- Dr. Alex Finkral (Northern Arizona University) co-I

Dr. Kristin Byrd (Kristin) has expertise in California riparian systems and is an ecological modeler with significant experience in ecological restoration efforts. Kristin will participate in the development of a high resolution riparian vegetation map of the study areas. Also supported by spatial analysis skills, Kristin is well positioned to take the outputs from sub-groups A-E and use them to develop a hydrological-ecological model of riparian productivity. This model will relate discharge of agricultural drainage water to riparian productivity and production of plant litter and detritus, a key component of juvenile salmonid food webs. To understand hydrological connections between cropland and dominant riparian vegetation, Kristin will identify riparian water sources (stream vs. groundwater) in key areas through stable isotope sampling. Kristin will further demonstrate the ecological consequences and restoration opportunities that increased crop water productivity generates for riparian vegetation. She will analyze alternative scenarios of water use and productivity in agricultural systems to assess potential implications for existing riparian areas. Through a partnership with the San Joaquin River National Wildlife Refuge, Kristin will explore the application of riparian water use maps for future riparian restoration planning in the Central Valley, given a warming climate. Dr. Alex Finkral (Alex) is a natural resources and silviculture expert with excellent knowledge of riparian ecosystems, their water, carbon, and ecosystem roles. Alex will guide the post docs at NAU on use of ecological indicators in ET (water use) and water productivity models.

Salaries and Wages of Staff for Sub-group D
Name: Dr. Kristin Byrd
Title: Research Geographer (Responsibilities: ecological modeling, ecological restoration, study of implications of various quanta of water available on fish and wildlife)
Organization: U.S. Geological Survey
Proposed efforts Year 1: 3.0 person-months (0.25 FTE)
Proposed efforts Year 2: 3.0 person-months (0.25 FTE)
Proposed efforts Year 3: 3.0 person-months (0.25 FTE)

Name: Dr. Alex Finkral
Title: Assistant professor (Responsibilities: study of natural resources along the riparian system: their carbon, water, ecosystem value, ecological modeling, ecological restoration, study of implications of various quanta of water available on fish and wildlife)
Organization: Northern Arizona University
Proposed efforts Year 1: 1.2 person-months (0.10 FTE)
Proposed efforts Year 2: 1.2 person-months (0.10 FTE)
Proposed efforts Year 3: 1.2 person-months (0.10 FTE)

Sub-group E: Phenology
- Dr. Cynthia Wallace (USGS)- Lead co-I
- Graduate student (TBD, University of Arizona) Phenology-climate

Dr. Cynthia Wallace (Cynthia) is an expert in phenological studies and remote sensing. She works in close coordination with the National Phenology Network (NPN) and has organized major National workshops on phenology and remote sensing. Cynthia’s main role will be to look through time (1982-2012) to study phenological changes in California agriculture based on time series remotely sensed data. She will look at whether a particular area has changed from: (a) single crop to double crop, (b) double crop to single crop, and (c) non-cropland to cropland. She will also look at signs for whether the changes have occurred from: (a) rainfed to irrigated, (b) surface irrigated to ground water irrigated. Other changes like change from one crop type (e.g., rice) to others (e.g., mixed) cropping will also be studies. The changes as a result will have implications for water use and will help sub-groups A, B, and C.

A graduate student (University of Arizona) in multi-temporal satellite sensor data analysis will work 50% of her/his time developing algorithms and running them to establish phenological changes and their implications.

The graduate student will get data support and advice from post doc 1 (water productivity and remote sensing) and post doc 2 (ET\water use modeling.

Cynthia and her team will also use advanced methods like spectral matching techniques (SMTs) and code them to automatically detect changes in phenology and find causes for the same.

Salaries and Wages of Staff for Sub-group E
Name: Dr. Cynthia Wallace
Title: Research Geographer (Responsibilities: study of phenology using time-series satellite sensor data from 1982-2012; develop automated algorithms for phonological studies, establish nature of phenological changes, indicate the implication of phenological changes on water availability and water use)
Organization: University of Arizona
Proposed efforts Year 1: 1.0 person-months (0.08 FTE)
Proposed efforts Year 2: 1.0 person-months (0.08 FTE)
Proposed efforts Year 3: 1.0 person-months (0.08 FTE)

Name: graduate student (phenology, remote sensing)
Title: Graduate student
Organization: University of Arizona (UoA)
Proposed efforts Year 1: 6.0 person-months (0.5 FTE)
Proposed efforts Year 2: 6.0 person-months (0.5 FTE)
Proposed efforts Year 3: 6.0 person-months (0.5 FTE)

**Sub-group F: Sub-group 6 (Scenario analysis)**

- **Dr. Peter H. Gleick** (Pacific Institute)- Project advisor
- **Dr. Juliet Christian-Smith** (Pacific Institute)- Scenario analysis, climate downscaling
- **Dr. Heather Cooley** (Pacific Institute)- Scenario analysis, climate downscaling

This sub-group, lead by Pacific Institute (California) and Dr. Juliet Christian-Smith (Pacific Institute) will: (a) provide various scenarios of water to better understand the consequences of choices or policies on a wide range of plausible future conditions; (b) simulate “new water” saved through various scenarios such as: (i) improved WP and (ii) re-allocation of crops (e.g., growing wheat instead of rice); and (c) identify spatially where we could gain "new water" and the opportunities for restoration based on climate projections.

Name: Dr. Peter H. Gleick
Title: President (Responsibilities: Project advisor and insights on water savings)
Organization: Pacific Institute
Proposed efforts Year 1: 0.72 person-months (0.06 FTE)
Proposed efforts Year 2: 0.72 person-months (0.06 FTE)
Proposed efforts Year 3: 0.72 person-months (0.06 FTE)

Name: Dr. Juliet Christian-Smith
Title: Senior Researcher Associate (Responsibilities: scenario analysis, climate downscaling-water availability assessment)
Organization: Pacific Institute
Proposed efforts Year 1: 1.68 person-months (0.14 FTE)
Proposed efforts Year 2: 1.68 person-months (0.14 FTE)
Proposed efforts Year 3: 1.68 person-months (0.14 FTE)

Name: Ms. Heather Cooley
Title: Researcher Associate (Responsibilities: scenario analysis, climate downscaling-water availability assessment)
Organization: Pacific Institute
Proposed efforts Year 1: 1.68 person-months (0.14 FTE)
Proposed efforts Year 2: 1.68 person-months (0.14 FTE)
Proposed efforts Year 3: 1.68 person-months (0.14 FTE)
Sub-group G: End Users/Conservation Leadership

- Eric Hopson (San Joaquin River National Wildlife Refuge, California) Lead end user

Eric Hopson is the refuge manager at the San Joaquin River National Wildlife Refuge, California. He is involved in coordinating restoration and conservation programs at the Refuge. He would like to work with the project team to use the project end results (e.g., water productivity maps, water use maps, riparian productivity model) to benefit ecological conservation and management efforts.

Salaries and Wages of Staff for Sub-group G

Name: Eric Hopson  
Title: Refuge Manager, San Joaquin River National Wildlife Refuge, California
(Responsibilities: working with project team to create Fish and Wildlife conservation scenarios to varied water availability)

Organization: U.S. Geological Survey

Proposed efforts Year 1: $6500 for travel to meetings with project team members  
Proposed efforts Year 2: $6825 for travel to meetings with project team members  
Proposed efforts Year 3: $7166 for travel to meetings with project team members

12.1 Fringe benefits of Staff (budget sub-sections: 12.1.2, 12.2.2, 12.3.2) from various Sub-groups listed below

USGS fringe benefits vary between 22-28% depending on the position and location
University of Tennessee fringe benefits vary between 28-28% depending on the position
Northern Arizona University fringe benefits vary between 16-35% depending on the position

These are according to existing norms of the Institutes concerned.

12.1.4 Field work, data collection and synthesis, travel

The project will need extensive data collection in order to ensure building robust and accurate water productivity models and maps. There are 4 distinct types of data that will be gathered during the project. These are:

A. Field plot data on crop and riparian vegetation biophysical quantities;  
B. Meteorological data for potential/reference ET (water use) calculations for crops and riparian;  
C. Water delivery data to determine irrigation efficiency and establish water balance;  
D. Actual ET measurements in the field for evaluations and validations of water use (ET) models built using remote sensing;  
E. Secondary data such as precipitation, temperature, elevation.

Many of these data are available from various sources (e.g., Table B1, Figure B1). But the field-plot data on crop biophysical and yield as well as crop and riparian vegetation characteristics (e.g., Table B1) need to be collected from specific locations, representing various crops and
vegetation and making precise measurements from specific locations in order to build robust models and for validation of these models.

**Table B1 Sources and characteristics of water delivery, meteorological and field-plot data**

<table>
<thead>
<tr>
<th>Data</th>
<th>Freq.</th>
<th>Source or equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Field plot</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PAR and LAI, narrowband meas.</td>
<td>4-5x per</td>
<td>AccuPAR LP-80, ASD Spectroradiometer.</td>
</tr>
<tr>
<td>Biomass/area (wet &amp; dry)</td>
<td>growing season</td>
<td>Harvest of field plot</td>
</tr>
<tr>
<td>Geographic coordinates</td>
<td></td>
<td>Digital camera/Notebook</td>
</tr>
<tr>
<td>Crop descriptions</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Meteorology</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar rad., air temp., soil temp., rel. humidity, wind speed, precipitation</td>
<td>Hourly</td>
<td><a href="http://www.cimis.water.ca.gov">www.cimis.water.ca.gov</a> CIMIS measurement stations</td>
</tr>
<tr>
<td><strong>Water delivery</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irrigated crop acres and water use (from statewide surveys)</td>
<td>Annual</td>
<td><a href="http://www.landwateruse.water.ca.gov/">www.landwateruse.water.ca.gov</a> + CVP, CSWP, ACWA</td>
</tr>
<tr>
<td><strong>ET</strong>&lt;sub&gt;a&lt;/sub&gt; measurements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lysim., Bowen ratio, scintillometer (CIMIS)</td>
<td>daily</td>
<td><a href="http://www.cimis.water.ca.gov">www.cimis.water.ca.gov</a> CIMIS measurement stations</td>
</tr>
<tr>
<td><strong>Secondary data</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Precipitation, temperature, Geology, soil, etc.</td>
<td>various time periods</td>
<td>USGS + Offices mentioned above</td>
</tr>
</tbody>
</table>

Institution acronyms: Central Valley project (CVP), Cal. State Water Project (CSWP), Association of California Water Agencies (ACWA), Department of Water resources (DWR).

**Figure B1. San Joaquin CDWR (California Department of Water Resources) district with State and inter-state (dashed lines) and CIMIS (California Irrigation Management Information System) meteorological stations (dots).**
Extensive field data will be gathered to calibrate and validate the crop productivity models. Ground data will be gathered over two growing seasons (approx. mid-February through November), with four to five surveys per season (1x early growth, 1x or 2x mid-growth, 1x tasselling, 1x senescing), as shown in Table B2. The exact dates will be fixed according to optimal satellite overpass dates of various sensors and the growth pattern of each crop type. 75% of the points will be used for modeling, and the remaining 25% for validation. The investigated crop types (wheat, cotton, alfalfa, rice, corn, grapes) cover over half the total irrigated area (about 10 million acres). Approximately 50 spatially explicit sample site locations for each of the 6 crop types will be selected. An initial agreement with the landowners on the location of survey plots will be sought prior to fieldwork. The meteorological network of the California Irrigation Management Information System (CIMIS) will provide the additional data required for modeling crop yield.

Table B2. Provisional field survey calendar with 5 campaigns (of 5 to 10 days) in grey.

<table>
<thead>
<tr>
<th></th>
<th>J</th>
<th>F</th>
<th>M</th>
<th>A</th>
<th>M</th>
<th>J</th>
<th>J</th>
<th>A</th>
<th>S</th>
<th>O</th>
<th>N</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Data will be collected in each 5-10 days campaign and will include **crop parameters** such as photosynthetically active radiation (PAR) and leaf area index (LAI) ($m^2/m^2$) measurements through an AccuPAR LP-80 ceptometer, as well as **narrowband measurements** with an ASD spectroradiometer. These will be carried out along 30 m transects. Plots of 10 $m^2$, will be harvested: the wet and dry biomass (Kg) will be measured by weighing - on site and in the lab (oven 70 °C), respectively. Observations of plant conditions, (e.g. height, growth stage, cover fraction) will be recorded and digital photographs taken. **Meteorological data** that will be retrieved from existing stations are: air temperature, relative humidity, solar radiation, wind speed and precipitation. The CIMIS network will allow having a station within a radius of 10 km of any ground truth point. An initial effort will be made to inventory existing cropland lysimeters, and Bowen ratio towers, and seek an agreement to make use of CIMIS’ scintillometer. Every sample and measurement point will be located with a GPS. For each crop type, a ‘representative area’ will be delineated and precise ground truth sites located within its perimeter for routine gathering of data. These areas will be located along the State Route 99, between Fresno and San Joaquin, where all studied crops are present and in the vicinity of USGS station locations. The optimum sampling network will minimize driving distance and maximize environmental variability (e.g. soil, irrigation technique) of the crops. Sampling locations and dates will be precisely determined at the onset of, or even prior to, the project.
**Budget: for 3 years**

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Year 1</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Data collection</strong></td>
<td>Ceptometer AccuPAR LP-80, Laptop computer for data collection, GIS, etc.</td>
<td>4,600</td>
</tr>
<tr>
<td></td>
<td>Gasoline brush cutter for harvesting</td>
<td>1,800</td>
</tr>
<tr>
<td></td>
<td>Digital camera</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>Hanging scale</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Field supplies: consumables and cheap items, e.g. sample bags, tape measure,</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>rope, sledge hammer, ladder</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Satellite imagery (free access through USGS)</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Spectroradiometer (free access through USGS)</td>
<td>0</td>
</tr>
<tr>
<td><strong>Data analysis</strong></td>
<td>Oven (sample drying)</td>
<td>1,000</td>
</tr>
<tr>
<td></td>
<td>Desktop computer (large RAM and good processor)</td>
<td>3,600</td>
</tr>
<tr>
<td></td>
<td>Software Matlab, ArcGIS, Erdas Imagine and ERMapper (free license through USGS)</td>
<td>0</td>
</tr>
<tr>
<td><strong>Travel</strong></td>
<td>Fieldwork, food, board &amp; lodge: 1 campaign of 10 days and 4 campaigns of 5</td>
<td>13,800</td>
</tr>
<tr>
<td></td>
<td>days at 115$/day for 4 people</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fieldwork mileage: 1 campaign of 2500 miles (fuel: 600$) and 4 campaigns of</td>
<td>1,800</td>
</tr>
<tr>
<td></td>
<td>1200 miles (fuel: 300 $)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Conference presentation/travel and per diem: 4 persons</td>
<td>3,300</td>
</tr>
<tr>
<td></td>
<td>Vehicle (free access through USGS)</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Air-fare for PI and Co-Is : 5 people, 1 trip per year</td>
<td>7,200</td>
</tr>
<tr>
<td></td>
<td>(includes Board, lodge, per diem for 5 days * 5 persons)</td>
<td></td>
</tr>
<tr>
<td><strong>Visit to institutes</strong></td>
<td>Road, board &amp; lodge close to institute (e.g. CIMIS, and Pacific Institute),</td>
<td>1,700</td>
</tr>
<tr>
<td></td>
<td>15 days with a 115$ per diem: 2 persons</td>
<td></td>
</tr>
<tr>
<td><strong>Farmer</strong></td>
<td>A local farmer will be hired to coordinate activities by getting agreements</td>
<td>9,600</td>
</tr>
<tr>
<td></td>
<td>with set of farmers to allow us into their fields to conduct research and</td>
<td></td>
</tr>
<tr>
<td></td>
<td>take samples. The farmer will be hired for 8 weeks, working 40 hrs a week at</td>
<td></td>
</tr>
<tr>
<td></td>
<td>@ 30 per hour</td>
<td></td>
</tr>
<tr>
<td><strong>Total (Year 1) $</strong></td>
<td></td>
<td>49,600</td>
</tr>
</tbody>
</table>
### Year 2

**Data collection**
- Ceptometer AccuPAR LP-80
- Laptop computer for data collection, GIS, etc.
- Gasoline brush cutter for harvesting
- Digital camera
- Hanging scale

Field supplies: consumables and cheap items, e.g. sample bags, tape measure, rope, sledge hammer, ladder  
Satellite imagery (free access through USGS)  
Spectroradiometer (free access through USGS)

<table>
<thead>
<tr>
<th></th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oven (sample drying)</td>
<td>1,000</td>
</tr>
<tr>
<td>Desktop computer (large RAM and good processor)</td>
<td>0</td>
</tr>
<tr>
<td>Software Matlab, ArcGIS, Erdas Imagine and ERMapper (free license through USGS)</td>
<td>0</td>
</tr>
</tbody>
</table>

**Data analysis**
- Oven (sample drying)  
- Desktop computer (large RAM and good processor)  
- Software Matlab, ArcGIS, Erdas Imagine and ERMapper (free license through USGS)

<table>
<thead>
<tr>
<th></th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oven (sample drying)</td>
<td>1,000</td>
</tr>
<tr>
<td>Desktop computer (large RAM and good processor)</td>
<td>0</td>
</tr>
<tr>
<td>Software Matlab, ArcGIS, Erdas Imagine and ERMapper (free license through USGS)</td>
<td>0</td>
</tr>
</tbody>
</table>

**Travel**
- Fieldwork, food, board & lodge: 1 campaign of 10 days and 4 campaigns of 5 days at 115$/day for 4 people  
- Fieldwork mileage: 1 campaign of 2500 miles (fuel: 600$) and 4 campaigns of 1200 miles (fuel: 300 $)  
- Conference presentation/travel and per diem: 4 persons  
- Vehicle (free access through USGS)  
- Air-fare for PI and Co-Is: 4 people, 1 trip per year  

<table>
<thead>
<tr>
<th></th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fieldwork, food, board &amp; lodge: 1 campaign of 10 days and 4 campaigns of 5 days at 115$/day for 4 people</td>
<td>13,800</td>
</tr>
<tr>
<td>Fieldwork mileage: 1 campaign of 2500 miles (fuel: 600$) and 4 campaigns of 1200 miles (fuel: 300 $)</td>
<td>1,900</td>
</tr>
<tr>
<td>Conference presentation/travel and per diem: 4 persons</td>
<td>3,800</td>
</tr>
<tr>
<td>Vehicle (free access through USGS)</td>
<td>0</td>
</tr>
<tr>
<td>Air-fare for PI and Co-Is: 4 people, 1 trip per year</td>
<td>5,100</td>
</tr>
</tbody>
</table>

**Visit to institutes**
- Road, board & lodge close to institute (e.g. CIMIS, and Pacific Institute), 15 days with a 115$ per diem: 2 persons

<table>
<thead>
<tr>
<th></th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road, board &amp; lodge close to institute (e.g. CIMIS, and Pacific Institute), 15 days with a 115$ per diem: 2 persons</td>
<td>1,400</td>
</tr>
</tbody>
</table>

**Farmer**
- A local farmer will be hired to coordinate activities by getting agreements with set of farmers to allow us into their fields to conduct research and take samples. The farmer will be hired for 8 weeks, working 40 hrs a week at @ 30 per hour

<table>
<thead>
<tr>
<th></th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>A local farmer will be hired to coordinate activities by getting agreements with set of farmers to allow us into their fields to conduct research and take samples. The farmer will be hired for 8 weeks, working 40 hrs a week at @ 30 per hour</td>
<td>9,600</td>
</tr>
</tbody>
</table>

**Total (Year 2) $**

<table>
<thead>
<tr>
<th></th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total (Year 2) $</td>
<td>37,100</td>
</tr>
</tbody>
</table>
### Year 3

<table>
<thead>
<tr>
<th><strong>Data collection</strong></th>
<th></th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceptometer AccuPAR LP-80</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Laptop computer for data collection, GIS, etc.</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Gasoline brush cutter for harvesting</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Digital camera</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Hanging scale</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Field supplies: consumables and cheap items, e.g. sample bags, tape measure, rope, sledge hammer, ladder</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Satellite imagery (free access through USGS)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Spectroradiometer (free access through USGS)</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Data analysis</strong></th>
<th></th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oven (sample drying)</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Desktop computer (large RAM and good processor)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Software Matlab, ArcGIS, Erdas Imagine and ERMapper (free license through USGS)</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Travel</strong></th>
<th></th>
<th>4,600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fieldwork, food, board &amp; lodge: 1 campaign of 10 days at 115$/day for 4 people</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Fieldwork mileage: 1 campaign of 1200 miles (fuel: 600$)</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>Conference presentation/travel and per diem: 4 persons</td>
<td>3,400</td>
<td></td>
</tr>
<tr>
<td>Vehicle (free access through USGS)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Air-fare for PI and Co-Is: 4 people, 1 trip per year (includes Board, lodge, per diem for 5 days * 5 persons)</td>
<td>5,100</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Visit to institutes</strong></th>
<th></th>
<th>1,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road, board &amp; lodge close to institute (e.g. CIMIS, and Pacific Institute), 15 days with a 115$ per diem: 2 persons</td>
<td>1,000</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Farmer</strong></th>
<th></th>
<th>9,600</th>
</tr>
</thead>
<tbody>
<tr>
<td>A local farmer will be hired to coordinate activities by getting agreements with set of farmers to allow us into their fields to conduct research and take samples. The farmer will be hired for 8 weeks, working 40 hrs a week at @ 30 per hour</td>
<td>9,600</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total (Year 3) $</th>
<th></th>
<th>24,300</th>
</tr>
</thead>
</table>
12.1.5 **OTHERS**
The project will require budget for:

Postage and freight. Since the Co-Is are located in different offices, coordination and communication will require an estimated cost of $450 for each year.

Printing and copying. Printing of posters for conferences and presentation and copying for meetings. There is also significant cost involved in copying field forms for each field visit. We estimate a cost of $600 for each year.

Supplies and services. These will include notebooks and stationary for field campaigns, pen drives for field data backup during field missions, and regular office supplies like paper, pens, ink cartridge. We estimate $900 for year 1 and $500 each for year 2 and 3.

12.1.6 **Data acquisition and equipment**
**Satellite sensor data**: A set of four sensors has been selected to provide the following information: hyperspatial data (Geoeye-1\Quickbird\IKONOS), hyperspectral data (Hyperion), high resolution-large swath images (Rapid Eye), and medium resolution multispectral images (Landsat, ALI) – see Table B3. Requirements are that data must be regularly available over the growing season, and cover the irrigated croplands of California. Should any problem prevent the use of one of these sensors, other sensors would be available (Table B3).

<table>
<thead>
<tr>
<th>Selected satellite sensors</th>
<th>Spatial resolut.</th>
<th>Revisit</th>
<th>Type</th>
<th>Swath</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>E01 ALI</td>
<td>30 (pan 10) m</td>
<td>16 days</td>
<td>Multispec.</td>
<td>37 km</td>
<td>USGS</td>
</tr>
<tr>
<td>E01 Hyperion</td>
<td>30 m</td>
<td>16 days</td>
<td>Hyperspec.</td>
<td>8 km</td>
<td>USGS</td>
</tr>
<tr>
<td>Rapid Eye</td>
<td>6.5 m</td>
<td>1-5.5 days</td>
<td>Hyperspat.</td>
<td>77 km</td>
<td>USGS</td>
</tr>
<tr>
<td>Geoeye-1</td>
<td>1.7 (pan 0.4) m</td>
<td>&lt;3 days</td>
<td>Hyperspat.</td>
<td>15 km</td>
<td>USGS</td>
</tr>
</tbody>
</table>

Alternative satellite sensors

| Quickbird                  | 2.4 (pan 0.6) m  | 3.5 days | Hyperspat.| 17 km | USGS   |
| IKONOS                     | 4 (pan 1) m      | 3.5-5 days | Hyperspat.| 11 km | USGS   |
| Landsat ETM+               | 30-90 (pan 15) m | 16 days | Multispec.| 185 km| USGS   |

Exhaustive strategies to acquire hyperspectral, hyperspatial, and advanced multispectral data are in place. First, we have free access to the entire archive of commercial high resolution imagery (Quickbird, IKONOS, Geoeye-1) through two US Govt. sources: (a) Commercial Imagery Derived Requirement (CIDR) Database of USGS, and (b) National Geospatial Intelligence Agency (https://warp.nga.mil/). Second, the entire archive of EO-1 Hyperion and ALI imagery became web-enabled (free) starting July 1, 2009. Third, we will use ASD spectroradiometer (400-2500 nm) available from the USGS to gather hyperspectral data of regrowth of vegetation. Fourth, a wall-to-wall coverage of web-enabled Landsat data for California is available for free.
Given the above facts, only a nominal cost of $5,200 for year 1 and the same for year 2 is required for satellite sensor data acquisition. This cost is mainly for Rapideye and Geoeye data for which we still have to pay.

The volume of data will be several terabytes (from multiple sensors with repeat acquisitions for 2 years + processed data + products + backups). In addition, all the ground data, meteorological data, and water data will be standardized and harmonized for the project. In addition to existing storage capacity within the USGS, we need to specifically safeguard data of this project and host essential products on public domain. We estimate a cost of $14,400 for a 20 TB RAID drive. Additional capacity during year 2 and year 3 for backups is estimated as $4500 and $3200.

Two high end desk top computers will be purchased for the 2 post docs each costing $4700 for a total of $9200 during year 1. The computers will be required for satellite data processing, modeling, and mapping.

The total costs of storage, backup, computers, and satellite sensor data acquisition will be: $28,800 during year 1, $9,700 during year 2, and $3,200 during year 2.

12.1.7 Indirect costs
The USGS charges indirect costs of 54.25% for all projects as a general norm. An administrative costs of transferring dollars from USGS to UoT and NAU will be 6%. These percentages are factored in the total budgets (see the spreadsheet).

12.3.3 Post doctoral scholar expenses
There will be 2 post doctoral scholars- playing a major role in the project. The post doctoral scholars will be hired for following major tasks:

Post doctoral scholar 1 (water productivity modeling): The main roles of this post doc will be:
  - Crop type classification, riparian classification at various resolutions
  - Crop productivity modeling
  - Crop productivity mapping
  - Water productivity modeling
  - Water productivity mapping
  - Remote sensing data analysis for all the above tasks
  - Heavy computing, algorithm development

Post doctoral scholar 2 (water use\ET modeling and mapping): The main roles of this post doc will be:
  - ET (water use) modeling and mapping for crops and riparian systems
  - Refinement and advancement of ET models
  - Comparison of ET model results for all major ET models
  - Assessment of uncertainties in ET estimates

More specifically, both post docs will coordinate and work on:
  - Crop productivity modeling and mapping
    - Field data gathering, image data normalization
Building crop productivity models and maps for 5 major crops
Validation of crop productivity models and maps at various resolutions (taking hyperspectral, hyperspatial, and advanced multi-spectral data)

- Water use (ET) modeling and mapping
  ET modeling (water use) for agricultural crops and riparian vegetation
  Building a comprehensive meteorological and remote sensing database for ET modeling
  Validation of ET models and maps at various resolutions (using hyperspectral, hyperspatial, and advanced multi-spectral data)

- Water productivity modeling and mapping
  Develop water productivity models and maps
  Pinpoint areas of low and high water productivity
  Establish uncertainties and errors in water productivity (using hyperspectral, hyperspatial, and advanced multi-spectral data)

Both post docs will require powerful computers and data storage facilities. These have been budgeted and discussed in section 12.1.7.

In addition, the post docs will require office space, office supplies, and maintenance. For this $3600, $2800, and $2400 has been budgeted for years 1 and 2.

The 2 post docs and Dr. Finkral, will need to travel for project meetings to California (apart from the field trip in which the post docs will participate). The travel costs include: (a) for 3 of them 1 trip for a project meeting every year and (b) Dr. Finkral to attend a conference. Total travel costs (including air tickets, board and lodge) is estimated to cost $5100 for year 1 (3 days project meeting with a day of field visit for the entire team), $4800 for year 2 (3 days project meeting), and $4300 for year 3 (2 days project meeting).

12.2 Milestones and timeline
The project milestones and timeline are outlined below.
12.3 Deliverable products and timeline

The project has 14 deliverables in specified periods of the project as outlined below:

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Cover Page
Predicting and Preventing Crisis in Irrigated Water Use in a Changing Climate
Measuring, Modeling and Mapping Trends and Changes in Agricultural Water Productivity for California

Project Team: Each sub-group has project leads, senior researchers, post-docs, & graduate students:

A. Water productivity modeling, mapping and remote sensing
   - Dr. Prasad S. Thenkabail, PI, (USGS, water productivity mapping, project management)
   - Dr. Dong Wang, Collaborator, (USDA-ARS, California-crop water productivity mapping, water use)
   - Post doc 1 (Dr. V. Dheeravath, NAU, water productivity mapping and remote sensing)
   - Post doc 2 (TBD, NAU, water use/ET modeling, remote sensing)

B. Water use (actual ET) modeling
   - Dr. Pamela Nagler, co-I, (USGS, water use/ET modeling lead, project management)
   - Post doc 2 (TBD, NAU, water use/ET modeling, remote sensing)
   - Graduate student (TBD, University of Arizona, water use/ET modeling and remote sensing)

C. Hyperspectral remote sensing and uncertainty analysis in WP mapping
   - Dr. E. Terrence Slonecker, co-I, (USGS, hyperspectral remote sensing, uncertainty analysis)
   - Post doc 1 (Dr. V. Dheeravath, NAU, water productivity mapping and remote sensing)
   - Graduate student (TBD, USGS, remote sensing)

D. Phenology
   - Dr. Cynthia Wallace, co-I, (USGS, phenology)
   - Post doc 1 (Dr. V. Dheeravath, NAU, water productivity mapping and remote sensing)
   - Graduate student (TBD, University of Arizona, phenology)

E. Riparian productivity modeling
   - Dr. Kristin B. Byrd, co-I, (USGS, riparian vegetation, ecological restoration, project management)
   - Dr. Alex Finkral, co-I, (NAU, riparian vegetation, ecological restoration, project management)
   - Post doc 1 (Dr. V. Dheeravath, NAU, water productivity mapping and remote sensing)
   - Post doc 2 (TBD, NAU, water use/ET modeling)

F. Scenario analysis for “New Water” and climate and water availability
   - Dr. Peter H. Gleick, (Pacific Institute, Advisor to the project)
   - Dr. Juliet Christian-Smith, Senior Research Associate, (Pacific Institute, scenario analysis)
   - Heather Cooley, Research Associate, (Pacific Institute, scenario analysis)

G. End Users/Conservation Leadership
   - Eric Hopson, end user, (San Joaquin River National Wildlife Refuge, California)
   - Dr. Dong Wang, end user, (USDA-ARS, California-crop water productivity mapping, water use)
   - Sub-groups A to F
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Predicting and Preventing Crisis in Irrigated Water Use in a Changing Climate
Measuring, Modeling and Mapping Trends and Changes in Agricultural Water Productivity for California

Principal Investigator: Dr. Prasad S. Thenkabail, Research Geographer
Address: 2255, N. Gemini Drive, Flagstaff, AZ 86001, USA.
Telephone/fax number: 928-556-7221; Email: pthenkabail@usgs.gov; thenkabail@gmail.com
Duration of project: 3 years (February 1, 2010-January 31, 2013)
Annual funding requested from CALFED: $643,551 yr 1, $624,184 yr 2, and $616,773 yr 3.
Total funding requested from CALFED: $1,884,508 over 3 years.
Category: Topic 3: Coupled Hydrologic and Ecosystem Models.

Abstract: Global climate change presents challenges for mitigating and adapting natural resource use and management locally and regionally. In the case of decreased water availability, we propose a new and innovative approach of water productivity (WP, productivity per unit of water or kg/m³) mapping using advanced remote sensing data (hyperspectral-hyperspatial-advanced multispectral) that “pin-points” climate-induced water loss and/or areas of poor cropland WP. This in turn will lead to informed application of management practices and associated water savings exactly where they are needed. A study conducted in the irrigated croplands of the Central Valley of California will be ideal for demonstrating the linkages between water, climate, and food that are critically important, both ecologically and economically. Therefore, the central strategy of this action research will be to build advanced remote sensing, surface energy balance modeling, and scenario modeling to identify areas of probable WP problems and to quantify the volume of “new water” that will be made available if we increase WP in the irrigated agricultural areas of the Central Valley of California. This “new water” can then be diverted to environmental and urban uses or simply held as a “water bank” for lean years. A complementary goal will be to use a systems approach to determine the ecological outcome of increased water productivity in existing and restored riparian areas. The approach involves: (a) water use (actual ET; m³/m²) mapping through surface energy balance models, (b) crop and riparian productivity (productivity per unit area or kg/m²) mapping through spectro-biophysical modeling and interpolating the same to larger areas using remote sensing, (c) WP mapping by dividing crop productivity by water use, and (d) scenario analysis for “new water” through spatial modeling. Data products will serve as inputs to a hydrological-ecological model that relates discharge of agricultural drainage water to riparian productivity and production of plant litter and detritus, a key component of juvenile salmonid food webs. Through spatial modeling, scenarios of improved irrigated cropland water productivity will be analyzed and potential consequences for adjacent existing and restored riparian areas will be determined, information decision-makers will need with increasing pressures on water resources.

Key words: Water productivity, water use, new water, climate mitigation, riparian productivity, and remote sensing.
1. BACKGROUND AND RATIONALE

One of CALFED’s primary objectives is to ensure more efficient and flexible use of water resources through an array of projects and approaches. Recent research (e.g., Platonov et al., 2008) has shown that the biggest possible saving in water is likely to come from growing more food with less water [increasing water productivity (WP) or “more crop per drop”]. Currently there are tremendous differences in the quantum of water used to produce a unit of grain within and between farm fields in various parts of the world as a result of different water and farmland management techniques (Zwart and Bastiaanssen, 2004). This opens up an opportunity to study the causes of differences in water use to produce a unit of grain, pinpoint areas where these differences occur, and develop approaches of increasing water productivity.

What is needed locally and regionally is a method to quantify water use and agricultural water productivity, and a way to supply this information for management decision-making such that water utility can be optimized (CCSP, 2007). Of the total available water in California, 84% goes to irrigated agriculture (Gleick, 2000; Hutson et al., 2004; Wiebe and Gollehon, 2006), where 350 different crops are grown on approximately 10 million acres (California Department of Water Resources) (Figure 1). According to USDA-NASS statistics, 35% to 65% of this irrigation water is lost as agricultural effluent and discharge to aquifers (Figure 2).

California’s Central Valley is dominated by agriculture but punctuated with narrow corridors of remnant, fragmented riparian ecosystems present along rivers, tributaries and drainage ditches. Riparian vegetation provides important energy subsidies to salmonid food webs by furnishing detritus to terrestrial invertebrates, a significant component of juvenile salmonids’ diet (Allan et al., 2003). Riparian vegetation can also buffer non-point source pollution in agricultural return flows before they discharge into streams (Lee et al., 2004). Representing only 2-15% of its historic range (RHJV, 2004), water development and reclamation projects eliminated much of the Valley’s riparian forests (Werner and Hendrix, 1984).

Presently, the interspersion of riparian corridors within the matrix of irrigated cropland creates conditions for hydrological connectivity from cropland to riparian areas and potential riparian dependencies on irrigation effluent. Along the Colorado River, waste spills have regenerated native cottonwood and willow trees in some riparian corridors and created backwater and marsh areas that support birds and other wildlife (Nagler et al., 2005). In the San Joaquin Valley return flow from irrigation is the vastly dominant source of groundwater recharge (Faunt, 2009). These return flows may be curtailed in the future due to climate change and out-of-basin water transfers, increased agricultural efficiency, and more optimal management of dams. Climate change impacts are creating uncertainties in water availability and agricultural production due to changes in seasonal climate patterns, reduced snowpack runoff, and over-exploitation of groundwater, and therefore can lead to great cause for concern for food security (Thenkabail et al., 2009a, 2009b). In contrast to free-flowing rivers, greater changes in discharge and water stress are projected in river basins impacted by dams such as in California, which will have far-reaching ecological effects (Palmer et al., 2008).

Through advanced remote sensing techniques, our research in California’s Central Valley will: (a) develop models and maps to quantify agricultural and riparian water productivity; (b) characterize, quantify, and pinpoint lost agricultural effluent water; (c) model hydrological connections between agricultural and riparian water use and terrestrial/aquatic linkages that are formed through riparian productivity and detritus contribution to streams and floodplains; and (d) through spatial modeling, analyze scenarios of improved irrigated cropland water productivity and assess potential consequences for adjacent existing and restored riparian areas, information decision-makers will need with increasing pressures on water resources.
Figure 1. Irrigated croplands of California (Source: Thenkabail et al., 2009a) consume over 80% of all human water use in the state using 41,922 million cubic meter of water of the 53,019 million cubic meter diverted from surface waters or pumped from groundwater for growing 350 different crops on about 10 million acres (Source: California Department of Water Resources).

2. OVERARCHING GOALS

The overarching goal of this proposed research is to develop methods and protocols for modeling and mapping water productivity (WP) in the irrigated croplands of California’s Central Valley and to quantify water savings that may be re-allocated to other urban, environmental, or agricultural uses (or simply stored in a “water bank”) using hyperspectral, hyperspatial, and advanced multi-spectral remote sensing data. These scenarios are critical to compare different allocation policies and their impacts on users, including the environment. It is important that these scenarios reflect the current political framework and projected climatic change in order to be relevant. A complementary goal will be to use a systems approach to determine the ecological outcome of increased water productivity in existing and restored riparian areas, including the provision of riparian plant detritus to salmonid food webs.

Thereby, the central strategy of our study will be to demonstrate quanta of “new water” that will be made available in a changing climate if we increase water productivity (WP) of currently low WP areas in the Central Valley. We will further demonstrate the ecological consequences and restoration opportunities that increased crop water productivity generates for riparian vegetation. The outcomes and methodologies from the proposed research can be a boon to water-use efficiency and water-related decision-making. The research will demonstrate the high quality of practical information provided by USGS on a critical and complex national issue of high societal importance.
Figure 2. (Top Figure) Water accounting in California. Reference ET for several crops (in/yr), and a map of Cibola NWR on the CA-AZ border depicts the interplay between riparian and agricultural ecosystem water. (Bottom Figure) Total available water in California is 38,400,000 acre-ft/yr (12.5 trillion gallons per year). Of this amount, 16% goes to the public supply and 84% to agricultural use. At a minimum, 35% of agricultural water becomes return flow. Source: USDA-NASS and USGS websites.
3. WATER PRODUCTIVITY ("CROP PER DROP")

3.1 Agricultural Water Productivity

Crop water productivity (WP) is a vital parameter to assess the performance of croplands (Liu et al., 2007). It can be represented in physical or economic units (Wesseling and Feddes, 2006). The physical crop WP (kg/m³) is the ratio of crop yield (ton/ha) to the amount of water used (m³/ha). The economic WP ($/m³) relates the economic benefits per unit of water used. The WP studies at different scales are the direction of investigation of many researchers in the world (Ahmad et al., 2004, Droogers and Kite, 1999). The first step in improving performance is to understand the levels, distribution, and patterns of WP.

The existing WP studies (Bouman et al., 2005; and Oweis et al., 2005) are generally conducted through four approaches. The first approach is field experiments that provide critical initial understanding of water productivity values. However, this method is time, labor, and money intensive (Ahmed et al., 2006) and spatial accuracies are questionable unless one has very large data samples. The second approach involves models such as Soil, Water, Atmosphere, and Plant (SWAP) and Decision Support System for Agro-technology Transfer (DSSAT) that focus on plant water cycling in soil as well as plant and atmosphere as continuous processes, and estimates yield as a response to these processes. Unavoidable assumptions impose uncertainties and errors to these model outputs (Platanov et al., 2008). The third approach tries to overcome these limitations by linking hydrological models with remote sensing providing the greatest potential for improved understanding of WP variations and the causes (Immerzel et al., 2008). The fourth approach goes another step forward and aims to employ remote sensing and Geographical Information Systems (GIS) to map WP across spatial and temporal scales. This approach estimates both yield and actual evapotranspiration (ET) using the Surface Energy Balance Model Algorithm for Land (SEBAL) (Zwart and Bastiaanssen, 2004). The remote sensing approach overcomes data scarcity and scale limitations in conventional studies, reduces uncertainties, and covers a large spatial domain over time. The inherent strength of remote sensing for WP mapping and the nascent state of its development in terms of methods and approaches, especially at various resolutions, offers an opportunity to conduct systematic studies on agricultural water management performance evaluation and determine their uncertainties, errors, and accuracies.

Given this understanding, the agricultural crop water productivity portion of the proposal is targeted to: (1) develop remotely sensed indices designed to “pin-point” areas of low and high WP along a north-south gradient across the Central Valley, (2) characterize, quantify, and pin-point lost agricultural effluent water, and (3) through spatial modeling, establish scenarios for various quanta of water that will be saved by increasing WP of the currently low WP areas.

3.2 Riparian Vegetation Water Use and Productivity

Timing and quantity of water are major determinants of growth and survival of riparian plants (Orians et al., 1999; McBride and Strahan, 1984). For example, female arroyo willow (Salix lasiolepis) plants disperse millions of small seeds annually that are dependent upon predictable spring floods and persistent soil moisture (Karrenberg et al., 2002; Sacchi and Price, 1992). The dominant pioneer riparian tree species in the Central Valley, Fremont cottonwood (Populus fremontii ssp. fremontii), Goedding’s black willow (Salix gooddingii), and narrow-leaved willow (Salix exigua), require coordination between seed release timing and peak spring runoff for seedling establishment (Stella et al., 2006).
However willows and poplars require perennial water sources to survive (Stromberg, 1993). With access to groundwater resources, mature riparian trees exhibit higher rates of photosynthesis over longer time periods compared to other vegetation types (Scott et al., 2006). Consequently high dry-season productivity of riparian trees leads to a large accumulation of surface litter (Scott et al., 2006). The productivity of riparian plants, especially trees, influences the forms and fluxes of organic matter to adjacent streams – thereby strongly impacting patterns of channel morphology, water flow, sedimentation, and habitat in rivers (Balian and Naiman, 2005).

The San Joaquin River National Wildlife Refuge (NWR; Figure A2.1 in Appendix II) in Stanislaus County, the focus of our riparian study, is situated where three major rivers (San Joaquin, Tuolumne and Stanislaus) join to create a key travel corridor for wildlife. The refuge contains one of California’s largest riparian forest restoration projects: 400,000 native trees such as willows, cottonwoods and oaks have been planted across 1,700 acres of river floodplain creating the largest block of contiguous riparian woodland in the San Joaquin Valley. Approximately 360 acres of restored riparian vegetation on the Refuge have been irrigated with agricultural tailwater, which is also used to manage adjacent seasonal wetlands (River Partners, 2006). This important riparian woodland habitat supports many rare birds, including Swainson’s hawks, sandhill cranes, and Aleutian cackling goose (now delisted due to the large, created, wintering habitat) and a diversity of breeding songbirds including the threatened least Bell’s vireo. It also supports rare mammals, such as the re-introduced endangered riparian brush rabbit and riparian woodrat.

To understand riparian water requirements and the influence of cropland irrigation on riparian vegetation, this research will (1) generate water use maps of dominant riparian trees by species and age class along a north-south gradient within the Central Valley, (2) determine the extent that agricultural return flows support primary productivity of riparian vegetation and how this association is distributed spatially, (3) within the San Joaquin River NWR, develop a focused hydrological-ecological model that relates discharge of agricultural drainage water to riparian productivity and production of plant litter and detritus, a key component of juvenile salmonid food webs (Allan et al., 2003; Carroll and Jackson, 2008; Frazey and Wilzbach, 2007; Lecerf et al., 2005; Wipfli, 2005), and (4) analyze scenarios of improved crop WP to assess potential ecological consequences and restoration opportunities for adjacent riparian areas.

3.3 Phenology of Agricultural Crops and Riparian Vegetation

Phenology, or the study of seasonally recurring biological events, is a way to capture the response of vegetation to the sum total of its environmental conditions (Schwartz 2003; Chen et al. 2004). Critical understanding of crop and riparian phenology is crucial for accurate assessment of water use and water productivity models. Understanding the phenological responses of riparian plants to changes in climate and hydrology, and how environmental differences contribute to phenological variation is increasingly important to riparian restoration ecologists (Seavy et al., 2009). Time-series satellite sensor data can be used to characterize the annual phenology of different crops and riparian vegetation (Figure 3), including establishing: (a) differences in phenologies between crops (e.g., cotton crop has longer growing period compared to corn); (b) intensities of different crops (e.g., single crop, double crop in a year); (c) seasonality (e.g., timing of water availability affects vegetation health and vigor); (d) magnitude of different crops (e.g., magnitude of wheat vs. cotton); and (e) type of riparian vegetation (e.g., different species have different water consumption patterns). These distinctive phenological characteristics quantified using remote sensing and tied to particular crops and dominant riparian
trees, have significantly varying water implications. For example, more water is used by crops grown twice a season (e.g., alfalfa), crops with a long growing season (e.g., cotton), particular crop types (e.g., rice is a known water guzzler) or by riparian vegetation dominated by a particular species (e.g., water willows use more than cottonwoods).

We will couple the observed satellite-based phenology and knowledge of crop type and species requirements to dynamically quantify and map the water use of the agricultural and riparian landscapes along a north-south gradient in the Central Valley. Such information is crucial to improve water productivity models of agricultural croplands and riparian vegetation. The improved models will help us explore water use scenarios that: (a) consume less water, (b) contribute toward a “water bank”, and (c) determine optimal solutions for agricultural food production as well as riparian vegetation maintenance and productivity. According to Barnett et al. (2008), observations reveal significant changes in the hydrological cycle of the western United States during the last half of the 20th century, of which up to 60% of the change is human-induced, suggesting a large potential for management actions to help offset impacts of projected climate changes. With phenological information, this research aims to identify the specific locations where management actions can be effective.

**Figure 3. Phenologies and water use of agricultural croplands and riparian vegetation using time-series remote sensing.** Water use of crops is dependent on factors such as: (a) type of crop or vegetation, (b) intensity (e.g., single, double, or continuous crop), (c) magnitude (e.g., how high is NDVI), and (d) seasonality (e.g., what is the NDVI magnitude in different seasons). Source: Dheeravath et al., 2009.
4. STUDY AREA AND DATASETS

4.1 Study Area

California has unique geography and a Mediterranean climate, which have enabled the state to become one of the most productive agricultural regions in the world in which about 350 different crops are produced. Most of the croplands are frequently or continuously irrigated. There are about 10 million acres of irrigated croplands in California, half of which produce rice, corn, wheat, alfalfa and cotton (Figure 1). These five crop types have global significance as they are grown worldwide and support populations totalling about 3 billion people globally. In California they account for an overwhelming proportion of the total amount of the State’s water use. According to USDA-NASS statistics, California’s top crop in terms of acreage is alfalfa hay for forage and it requires 10 million acre-ft/yr of water or ~32% of the water allocated for agriculture in the state.

We will develop models and methods in representative areas (10×10 km$^2$; Figure 4) of major cropland (rice, corn, wheat, alfalfa and cotton) and riparian system at various resolutions using hyperspectral, hyperspatial, and advanced multispectral data. Representative areas will be distributed along a north-south transect across the Central Valley to cover growing areas of each of the five crops and encompass climatic differences along a north-south gradient. This study will focus on riparian areas where Fremont cottonwood and willow species dominate.

Figure 4. Locations of the representative areas (e.g., A: Rice, B: Corn, C: Wheat, D: Alfalfa and E: Cotton) in the State of California (left Figure). Hyperspectral, hyperspatial, and advanced multispectral data of these areas will be routinely acquired. Field-plot data on irrigated crop and riparian characteristics (e.g., yield, biomass) will be gathered from 500+ sample locations. Water use and meteorological data will be gathered from various sources from existing network of stations (e.g., right Figure). The data will be used to develop water use and water productivity models of crops and riparian vegetation.
4.2 Data Sets Needed For Crop and Water Productivity Models

The study will gather six distinct types of data: (a) satellite sensor data, (b) secondary data (e.g. DEM and soil type maps, etc.), (c) meteorological data, (d) water withdrawal data, (e) isotope samples, and (f) field-plot data. These are discussed briefly below.

4.2.1 Satellite sensor data collection strategy and sources: We will acquire satellite sensor data across spatial, spectral, radiometric, and temporal resolutions. These data are categorized as (Table 1 with details in Appendix I): A. hyperspectral, B. hyperspatial, and C. advanced multispectral. Advanced multispectral Landsat ETM+ data will be acquired for the entire Central Valley. Hyperspectral (e.g., Hyperion, spectroradiometer-see letter of support for the later) and hyperspatial imagery (GEOEYE\Quickbird\IKONOS) will be acquired for the entire representative 10 km×10 km blocks of the five major crops (see Figure 4). These images will help establish exact crop areas of the five target crops (rice, corn, wheat, alfalfa and cotton; Figure 4) as well as other irrigated areas and riparian vegetation cover.

We (USGS) has free access to the entire archive of commercial high resolution imagery (Quickbird, IKONOS, Geoeye-1) through two US government sources: (a) Commercial Imagery Derived Requirement (CIDR) Database of USGS, and (b) National Geospatial Intelligence Agency (https://warp.nga.mil/). Second, the entire archive of EO-1 Hyperion and ALI imagery became web-enabled (free) on July 1, 2009. Third, we will use ASD spectroradiometer (400-2500 nm) available from the USGS to gather hyperspectral data of regrowth of vegetation. Fourth, a wall-to-wall coverage of web-enabled Landsat data is available for all.

4.2.2 Secondary data: Secondary data consists of ASTER derived digital elevation data (GDEM), average annual precipitation and temperature data for the 30-year period, soil types, and administrative boundaries, acquired from reliable sources (see Appendix I).

4.2.3 Meteorological data: Meteorological data retrieved from existing CIMIS stations (e.g., Figure 4) provide air temperature, relative humidity, solar radiation, wind speed and precipitation (http://wwwcimis.water.ca.gov/; Appendix I for details). An initial effort will be made to inventory existing cropland lysimeters, Bowen ratio towers, and CIMIS’ scintillometer-data from which will be used to validate satellite based water use and water productivity models.

Table 1. Characteristics of sensor data that will be used in this research (details in Appendix I).

<table>
<thead>
<tr>
<th>Satellite sensor</th>
<th>Wavelength range (µm)</th>
<th>Spatial resolution (m)</th>
<th>Number of band (#)</th>
<th>Revisit (days)</th>
<th>Radiometric resolution (bit)</th>
<th>Acquisition date (and season)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A. Hyperspectral</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>EO-1 Hyperion</strong></td>
<td>0.43-2.40</td>
<td>30</td>
<td>196</td>
<td>16</td>
<td>16</td>
<td>5 images per season</td>
</tr>
<tr>
<td><strong>B. Hyperspatial</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GeoEye-1</td>
<td>0.45-0.90</td>
<td>0.41-1.65</td>
<td>5</td>
<td>&lt;3</td>
<td>11</td>
<td>1 scene per month</td>
</tr>
<tr>
<td>IKONOS</td>
<td>0.45-0.93</td>
<td>1.0-4.0</td>
<td>5</td>
<td>3</td>
<td>11</td>
<td>covering 5 key</td>
</tr>
<tr>
<td>Quickbird</td>
<td>0.45-0.90</td>
<td>0.61-2.44</td>
<td>5</td>
<td>1-6</td>
<td>11</td>
<td>representative areas</td>
</tr>
<tr>
<td>Rapideye</td>
<td>0.44-0.85</td>
<td>5.0-6.5</td>
<td>5</td>
<td>1-6</td>
<td>16</td>
<td>of the 5 major crops.</td>
</tr>
<tr>
<td><strong>C. Advanced multispectral</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landsat TM</td>
<td>0.45-12.5</td>
<td>30</td>
<td>7/8</td>
<td>16</td>
<td>8</td>
<td>1 scene per month</td>
</tr>
<tr>
<td>EO-1 ALI</td>
<td>0.43-2.35</td>
<td>30</td>
<td>10</td>
<td>16</td>
<td>16</td>
<td>covering entire</td>
</tr>
<tr>
<td>ASTER</td>
<td>0.53-11.65</td>
<td>15-90</td>
<td>9</td>
<td>16</td>
<td>8</td>
<td>Central Valley.</td>
</tr>
<tr>
<td>MODIS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOD09Q1</td>
<td>0.62-0.876</td>
<td>250</td>
<td>2</td>
<td>1</td>
<td>12</td>
<td>maximum value</td>
</tr>
<tr>
<td>MOD09A1</td>
<td>0.62-2.16</td>
<td>500</td>
<td>7*36</td>
<td>1</td>
<td>12</td>
<td>composition.</td>
</tr>
</tbody>
</table>

*Modis 500m (Mod09A1) has 36 bands, but we considered only the first 7 bands.
4.2.4 **Water withdrawal and delivery data:** County-level water withdrawals data for irrigation of California State is available through a USGS database ([http://water.usgs.gov/watuse/](http://water.usgs.gov/watuse/)).

4.2.5 **Isotope samples of riparian vegetation:** Naturally-occurring, stable isotopes of oxygen and hydrogen ($^{18}$O and $^2$H) can be used to characterize sources of water used by riparian vegetation, to partition ET into evaporation and transpiration, and to aid in calculating water use efficiency (WP) (Williams et al., 2004; Yepez et al., 2003). Ground water, rain water, and surface supplies all have distinctive “signatures” with respect to $^{18}$O and $^2$H; furthermore, water extracted from plant stems indicates the sources of water accessed by the plant and water extracted from soil and the atmosphere over the canopy can be used to partition ET into its components. We will extract water from aquifers, soils, plant stems and atmospheric samples over plant canopies to construct quantitative budgets of riparian plant water use.

4.2.6 **Crop/riparian biophysical and yield data as well as spectroradiometer data:**

**Crop Data:** For the purpose of crop and water productivity mapping, extensive sets of crop biophysical and yield data will be gathered from 30-50 sample locations for each crop every 15-20 days over two growing seasons. These sample locations will be selected randomly from within the 10 km×10 km representative areas (Figure 1). The field campaign will be conducted at times that correspond with satellite (e.g. Landsat, GeoEye-1\IKONOS\Quickbird\RadipEye and EO-1) overpass dates over the study areas. Photosynthetically active radiation (PAR) and leaf area index (LAI) ($m^2/m^2$) will be measured through an AccuPAR LP-80 ceptometer, as well as narrowband spectral reflectance measurements with an Analytical Spectral Devices™ (ASD) spectroradiometer. These will be carried out along 30 m transects. For crops, plots of 10 $m^2$ will be harvested: the wet and dry biomass (kg) will be measured by weighing - on site (green) and in the lab (oven 70 °C), respectively. Plant conditions, (e.g. height, growth stage, cover fraction) will be recorded and digital photographs taken.

**Riparian Data:** Similar measurements will be taken at the same frequency and duration on cottonwood and dominant willow species within each 10 km×10 km representative area, and will also correspond with satellite overpass dates. Narrowband spectral reflectance, LAI, tree height, and diameter at breast height (1.3 m) measurements will be taken. Core samples at breast height and representative 1 $m^2$ biomass samples will also be collected to characterize plant biomass size and age. Litter traps will be installed to collect and measure tree litter production at monthly time intervals (Reid et al. 2008, Gawne et al. 2007).

5. **METHODS FOR WATER PRODUCTIVITY MODELS AND MAPS**

The first steps in defining strategies for improved water use efficiencies will be to quantify and map the water used by both agricultural and riparian landscapes, spatially and temporally. We present an innovative approach to WPM that couples field data with remote sensing data and performs spatial modeling to map: (a) water use (or actual evapotranspiration; $m^3/m^2$) of crops and riparian vegetation, and (b) water productivity (productivity per unit of water or crop per drop; $kg/m^3$) of croplands and riparian vegetation. Remote sensing approaches (Glenn et al., 2007) overcome data scarcity and scale limitations in conventional studies, reduce uncertainties, and cover large spatial areas. The WPM approach for agricultural crops is illustrated in Figure 5. The same approach will be applied to riparian areas.
5.1 Crop and Riparian Productivity Models and Maps (CRPMs)

The CRPMs will be determined using various remote sensing data (Table 1) and field-plot data (Table 2) by: (i) mapping crop types and dominant riparian vegetation types; (ii) modeling crop and riparian yield and/or biomass; and (iii) extrapolating models to larger spatial areas using crop and riparian models on remote sensing images.

5.1.1 Crop type mapping and riparian vegetation mapping: Delineating crop types or riparian vegetation categories is an important first step to ensure precise water use estimates from these land use classes. Detailed, high resolution crop and vegetation maps will be generated for the five 10 km×10 km representative areas. This aspect of the research will fuse Landsat ETM+, IKONOS, and Hyperion imagery, through Spectral-textural-temporal algorithms, which offer three advantages: (1) a data record of crop and riparian vegetation signatures (Hyperion), (2) high-resolution images for the textural characterization of crops and riparian vegetation (IKONOS), and (3) a wall-to-wall coverage along with a record of multi-spectral and multi-temporal phenology of irrigated areas (Landsat) and riparian vegetation (this we will do by extrapolating the understanding developed through models developed in 10 km×10 km representative areas). Harmonic analysis will be adopted to identify crop and riparian vegetation types (Jakubauskas et al., 2002) using the models developed by Geerken et al. (2005) based on conventional Fourier analysis and adopting a Fourier Filtered Cycle Similarity (FFCS) method. Mixed classes will be resolved using hierarchical mapping protocol based on decision tree algorithm (Wardlow and Egbert, 2008). Irrigated versus rainfed croplands or riparian vegetation types will be distinguished using spectral libraries (Rao, 2007) and ideal spectral data banks (Thenkabail et al., 2009, 2007a). Similar classes will be grouped by comparing ideal spectra using spectral matching techniques (see Thenkabail et al., 2007). The evaluation of classified crops and riparian vegetation will rely on ground data with an expected Kappa coefficient of 0.9-0.95, a measure of accuracy. Riparian mapping will build on the 2007 Sacramento River Riparian Map project and its classification scheme using California Native Plant Society vegetation alliances (http://www.sacramentoriver.org/sacmon/).

5.1.2 Modeling agricultural crop and riparian productivity [biomass, yield, and aboveground net primary productivity (ANPP)]: Two alternative approaches to modeling productivity will be tested (Figure 5): (1) establishing an empirical relationship between spectral reflectance and biomass (statistical approach); and (2) defining a theoretical model that describes reflectance as a function of several bio-physical parameters (physically-based models). The statistical approach will relate different wavebands to either popular vegetation indices (e.g., normalized difference vegetation indices (NDVIs), transformed vegetation indices (TVIs), soil adjusted vegetation indices (SAVI), crop moisture sensitive indices (CMSIs)) or advanced hyperspectral vegetation indices (HVIs) to establish crop and riparian biophysical and yield characteristics. The physically-based approach will compare two models: (A) the Scattering by Arbitrary Inclined Leaves model (SAIL) coupled with the radiative transfer model PROSPECT (Jacquemoud et al., 2009) or variations of it (e.g. PROSAIL; Jacquemoud et al., 2009), combined with a Look-Up Table approach for solving the inverse problem; and (B) the Surface Energy Balance Algorithm for Land (SEBAL) biomass growth routine that uses light-use efficiency and photosynthetically active radiation models.

Specific steps involve: (1) establishing hyperspectral, hyperspatial and advanced multispectral wavebands and indices that are most sensitive to crop and riparian vegetation growth; (2) establishing the best models for crop and vegetation growth and yield (crop-specific,
vegetation species-specific) using (a) statistical models and (b) physically-based models; (3) for crops, estimate and map the yield (e.g. ton/ha) using the Harvest Index concept; (4) for riparian vegetation, calculate annual woody biomass production by subtracting year 2011 standing tree biomass from year 2010 biomass estimated by remote sensing-based models; estimate ANPP by adding annual woody biomass production to annual litter fall dry weights (Cavalcanti and Lockaby, 2006); and (4) establish uncertainties, errors, and accuracies of these models.

Table 2. Agricultural crop and riparian biophysical and yield variables that will be measured from 30-50 sample locations from the representative areas throughout the years 2010 and 2011.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Variable</th>
<th>Unit</th>
<th>Observation Frequency</th>
<th>Spectral indices</th>
<th>S-B/Y model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice</td>
<td>LAI</td>
<td>m²/m²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Biomass</td>
<td>Kg/m²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yield</td>
<td>Kg/m² or ton/ha</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corn</td>
<td>LAI</td>
<td>m²/m²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Biomass</td>
<td>Kg/m²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yield</td>
<td>Kg/m² or ton/ha</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheat</td>
<td>LAI</td>
<td>m²/m²</td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>Biomass</td>
<td>Kg/m²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yield</td>
<td>Kg/m² or ton/ha</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cotton</td>
<td>LAI</td>
<td>m²/m²</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Biomass</td>
<td>Kg/m²</td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>Yield</td>
<td>Kg/m² or ton/ha</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alfalfa</td>
<td>LAI</td>
<td>m²/m²</td>
<td></td>
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<tr>
<td></td>
<td>Biomass</td>
<td>Kg/m²</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Yield</td>
<td>Kg/m² or ton/ha</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Willow</td>
<td>LAI</td>
<td>m²/m²</td>
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<tr>
<td></td>
<td>Biomass</td>
<td>Kg/m²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Litter</td>
<td>mgC/m²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cottonwood</td>
<td>LAI</td>
<td>m²/m²</td>
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<tr>
<td></td>
<td>Biomass</td>
<td>Kg/m²</td>
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<tr>
<td></td>
<td>Litter</td>
<td>mgC/m²</td>
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</tbody>
</table>

5.2 Water Use Models and Maps (WUMs) of Agricultural Crops and Riparian Vegetation

Currently, in California, WU (actual ET) is commonly estimated from reference ET, calculated from weather station data, and estimated crop coefficients (Allen et al., 2007) available from the California Irrigation Management Information System (CIMIS), which includes a network of over 120 weather stations. Because crop coefficients vary with crop growth rate, planting density, and management practices, they do not return actual crops’ WU (Trout & Johnson, 2007, Cooley et al., 2009). As a result, crop over-irrigation or under-irrigation occurs as a result of lack of spatial knowledge of water use and related water productivity (WP). This can be improved by use of remote sensing, which is capable to detect the spatial and temporal distribution of WU within and among crops by gathering information mostly on solar radiation, surface temperature, and emissivity.

5.2.1 Surface energy balance models using thermal data: Up to now, most remote sensing methods for plant water use have used thermal bands to estimate ET by the difference between air temperature and land temperature such as METRIC (Allen et al., 2007), SEBAL (Bastiaanssen et al., 1998), and SEBS (Senay et al., 2007; Figure 5). Generic equation is: \( R_n = H + G + ET \), where \( R_n \) = net surface radiation; \( H \) = sensible heat; \( G \) = soil heat flux; \( ET \) = evaporation (all terms are in W/m²). From the above input data, the values of net radiation,
vegetation index, albedo, roughness length, soil heat flux, and sensible heat flux are calculated. A study conducted in the Imperial Irrigation District of Southern California for the 1998 water year (Thoreton et al., 2009) has shown that ET estimates from SEBAL were more accurate than the crop coefficient approach from CIMIS, the latter being 14% higher than the former. These methods provide a snap-shot of evapotranspiration (ET) at the time of satellite overpass but lacks accuracy in discriminating ET over spectrally diverse vegetation types because of the complexity of modeling the surface resistance to heat transfer by the different vegetation covers and difficulty of obtaining frequent cloud/haze free thermal imagery.

5.2.2 Vegetation-index (VI) based models: Recent studies, however, have combined ground measurements of ET, meteorological variables, and vegetation indices (VIs) determined by satellite sensors to project plant water use over diverse biomes, including deserts (Groeneveld et al., 2007; Glenn et al., 2008), semiarid rangelands (Nagler et al., 2007), agricultural districts (Hunsaker et al., 2007; Kim and Hogue, 2008), riparian corridors (Nagler et al., 2005, 2009), rainforests (Juarez et al., 2008), and mixed landscape units at the regional (Leuning et al., 2008; Zhang et al., 2008) and global (Mu et al., 2007; Wang and Liang, 2008) scales of measurement. VI methods are valuable in projecting ET over longer time periods (weeks, months and years), using time-series images from frequent-return sensor systems such as MODIS on the Terra satellite. VI methods work due to the high correlation between plant transpiration and green foliage density measured by VIs (Cowling and Field, 2003; Glenn et al., 2007). Choudhury et al. (1994) showed that crop transpiration on a ground area basis (\(E_G\)) can be calculated as:

\[
E_G = ET_o \times VI^* 
\]

where \(ET_o\) is daily potential or reference crop ET determined from micrometeorological data from one of several possible methods, and \(VI^*\) is one of several possible VIs scaled between 0 (no vegetation) and 1 (full cover vegetation transpiring at \(ET_o\)). \(VI^*\) replaces the empirically-derived crop coefficient \((k_c)\), normally used in Equation (1) (Allen et al., 2007), with a parameter based on the actual state of the canopy. Properly calibrated, Equation (1) can accurately predict crop ET. For example, Hunsaker et al. (2007) found that wheat ET predicted from \(ET_o\) and NDVI was within 5% of values determined in a weighing lysimeter.

5.3 Phenological Algorithms using Spectral Matching Techniques

We will develop algorithms based on spectral matching techniques (SMTs) to derive phenol-metrics of croplands and riparian vegetation using time-series satellite sensor data (Thenkabail et al., 2007). The methods will include quantitative SMTs such as: (a) spectral correlation similarity, and (b) spectral similarity value. Several studies use time-series satellite sensor data to extract pheno-metrics, such as onset of greenness and time of maximum greenness, which describe the pattern of greenness at that location throughout the year (e.g., Figure 3). These pheno-metrics will then be used in water use models (Section 5.2). Analysis of the historical phenology of the various crops, adjacent natural landscapes and associated riparian areas will inform whether and how the dynamics of these various vegetated landscapes are linked. The phenology of natural vegetation adjacent to croplands will capture information about ambient environmental conditions for the locale, including the impact of amount and timing of precipitation. Comparing the phenology of croplands and adjacent natural landscapes on a yearly basis will reveal how well-coupled irrigation intensity is to the observed ambient environmental conditions and whether irrigation intensity is directly related to the vigor of riparian vegetation. Characterizing the linkages between the dynamics of the various vegetated landscapes will help calibrate and refine management actions related to active irrigation.
5.4 Water Productivity Models and Maps (WPMs) of Agricultural Crops and Riparian Vegetation

The WPMs (Platonov et al., 2008) are produced by dividing the crop and riparian productivity maps (CRPMs) with water use maps (WUMs):

\[
\text{Water Productivity Maps (kg/m}^3\text{)} = \frac{\text{yield (kg/m}^2\text{ or kg/pixel) or economic value (\$)}}{\text{water use (m}^3/\text{m}^2\text{ or m}^3/\text{pixel})}
\]

**Figure 5. Water productivity (WP) mapping protocol** for the Central Valley, California that will be used in this research. The WP maps will be produced for the five major irrigated crops as well as riparian vegetation which will “pin point” areas of high and low WP. The area under various levels of low WP will be established and the water savings scenarios when the low WP areas are converted to various higher WP levels will be determined and highlighted.
5.5 Identifying riparian water sources through isotope sampling

Sampling will be done in five representative areas located along the north-south Central Valley transects. Samples will include plant stem samples; aquifer samples; vadose zone soil samples; and atmospheric samples collected over plant canopies. These samples will be analyzed for $^{18}$O and $^2$H enrichment to determine sources of water used by plants, water use efficiency, and the fraction of ET attributed to evaporation and transpiration.

5.6 Riparian vegetation detritus contribution to stream reaches and floodplains

Quantities of coarse particulate detritus contributed from over story trees will be sampled using litter traps in all five representative sample areas, with greater intensity of sampling at the San Joaquin River NWR for use in the hydro-ecological model of riparian productivity (Reid et al. 2008, Gawne et al. 2007). Within the Refuge, litter traps will be placed in riparian forests representing various stages of succession, from newly planted restored areas to old growth riparian forest located along the Stanislaus River in the northern portion of the Refuge. For all litter traps, detritus will be collected monthly for one year, sorted and air dried. A sub-sample of plant litter will be ashed at $550^\circ$C to determine carbon content. Litter production sampling will contribute to the project’s remote sensing-based phenology studies by identifying varying times of seed release and maximum leaf fall across a north-south gradient.

In order to estimate the quantity and timing of riparian litter inputs to streams, statistical functions will be calculated to describe the quantity of litter produced by a given tree at a particular time (litter production) and the distance from the tree any piece of litter would travel as it fell (litter dispersion) (Gawne et al., 2007). Functions will be based on biophysical tree measurements, including LAI, DBH, and tree height. Litter inputs to the channel will then be estimated by incorporating these biophysical measurements for each reach. These estimates will provide a measure of carbon pools available from our study area.

5.7 Hydrological-Ecological Model of Riparian Productivity

Linkages between agricultural and riparian water use will be coupled with riparian biomass and litter production estimates to create a hydrological-ecological model of riparian productivity. Through monthly data collection, this model will establish the intra-annual connection between water availability and riparian carbon exports to the salmonid food web via litter production and dispersion. It will also establish for specific areas riparian carbon export dependencies on agricultural water sources. Figure 6 demonstrates how data products generated in this study will be applied in the development of this model.

Within the San Joaquin NWR, monthly estimates of riparian biomass and litter production for Fremont cottonwood and willow species by age class combined with analysis of carbon content of litter production will be used to estimate monthly estimates of carbon inputs for a given stream reach. Phenology studies will inform how biomass production varies with temperature and precipitation. Isotope analysis will determine sources of water used by plants, water use efficiency, and the fraction of ET attributed to evaporation and transpiration. Combined with riparian water use maps, the isotope analysis will determine what portion of water used is from agricultural sources. A dynamic measure of riparian water productivity will be calculated as a ratio of plant biomass or litter production (g/m$^2$) to water use (m$^3$/m$^2$).
Riparian water use maps, estimates of agricultural water discharge

$^{18}$O and $^2$H isotope samples of plant stems, soil, water and air to determine riparian water sources and fraction of ET attributed to evaporation and transpiration

Phenology studies to relate riparian biomass to precipitation, temperature patterns

Monthly estimates of biomass and litter production for Fremont cottonwood and willow

Carbon content of litter production by species and age class

Riparian water productivity calculations: Biomass or litter production (g/m$^2$)/water used (m$^3$/m$^2$)

Monthly estimates of carbon inputs for a given stream reach

Figure 6. Diagram of the Riparian Productivity Model. Data products from this study will serve as inputs to a hydrological-ecological model of riparian productivity that will relate discharge of agricultural drainage water to riparian productivity and production of plant litter and detritus, a key component of juvenile salmonid food webs (Allan et al., 2003; Carroll and Jackson, 2008; Frazey and Wilzbach, 2007; Lecerf et al., 2005; Wipfli, 2005).

6. UNCERTAINTIES, ERRORS, AND ACCURACIES IN WPMS:
A complete error analysis and validation is necessary in order to make effective use of the water productivity maps created in this project. The different models will be evaluated to see which produces the best results by examining descriptive statistics computed from the error matrix, such as overall, producer’s, and user’s accuracies (Congalton and Green, 2009; Figure 7).

Figure 7. Flow chart showing the process for accessing spatial uncertainty/map accuracy.
7. SCENARIO ANALYSIS

The Pacific Institute has been conducting scenario analysis of water use in California for many years. Their scenarios have informed the Department Water Resources’ Water Plan Update, which now explores multiple futures for water demand. It is important to be clear about the role of scenarios in water planning and research. Humans have always thought about possible futures, explored plausible paths, and tried to identify the advantages and disadvantages associated with different choices. In recent years this has led to a growing interest in scenarios, forecasting, and “future” studies (see, for example, Schwartz, 1991).

Scenario planning has more than academic implications. In the water sector, expectations about future water demands and supplies drive huge financial expenditures for water-supply projects. These projects, in turn, have significant human and ecological impacts. At the same time, failing to make necessary investments can lead to the failure to meet fundamental human water needs. The challenge facing water planners is to balance the risks and benefits of these kinds of efforts. Analysts and decision makers often construct scenarios to better understand the consequences of choices or policies on a wide range of plausible future conditions. This is particularly useful when there are great uncertainties about how the future may evolve, or when the stakes are especially high. Sometimes scenarios explore outcomes that are unlikely or incongruent with current decisions and policies. Scenarios are either descriptive or quantitative and represent discrete outcomes drawn from a range of possible futures.

A set of scenarios provides a broad look at how the future may evolve in response to (1) forces largely outside the control of policy makers, and (2) policy choices designed to shape future conditions. Such a “scenario analysis” approach can help resource managers and interested stakeholders better understand the inherent uncertainties about future management and, in turn, help reveal more innovative and successful management strategies for adapting to possible futures. Ultimately, the point—and power—of scenarios is not to develop a precise view or prediction of the future. It is to enable us to look at the present in a new and different way, and to find new possibilities and choices we might have previously overlooked or ignored.

Once WP maps are produced at different resolutions for the representative areas and extrapolated to Central Valley using the best models, we will build spatial models in ArcGIS 9.3 that will simulate “new water” saved through various scenarios (Byrd, 2009; Kooistra et al., 2008, Carpenter et al., 2005) such as: (a) improved WP and (b) re-allocation of crops (e.g., growing wheat instead of rice). The output of these models will provide visualization of where, when, and how much water is saved. In the representative 10 km x 10 km study areas where riparian primary productivity and riparian water sources are established, we will demonstrate the ecological consequences and restoration opportunities that increased crop water productivity generates for riparian vegetation, identify where ecosystems may be impacted by reduced return flows, and demonstrate how ecosystems could be supported with an additional water supply from agricultural return flow savings (possibly up to 30% more water). Maps of scenario outputs will be made publicly accessible via a USGS website that will contain a Web Mapping Service generated with ArcGIS Server 9.3. Users will be able to view and query, compare and contrast scenario maps, and generate customized maps from the website (e.g., http://landcovertrends.usgs.gov).

8. CLIMATE SCENARIOS AND WATER AVAILABILITY

In addition to contributing to the scenario analysis of crop water productivity, the Pacific Institute will also provide expertise in terms of the climate change context. Using downscaled temperature and precipitation data from global climate model outputs to the study regions (Figure 8.), we will determine impacts on water demand by incorporating changes in outdoor water use (driven by changes in evapo-transpiration rates) and crop yields. This model builds on previous work by the Pacific Institute, but would be more specific to characterizing changes in particular study sites and for individual crop types.

Figure 8. Change in California annual average temperature (a) and precipitation (b) for 2070-2100 period relative to 1960-1990 for different global climate models (published in Lobell et al., 2006).

9. RELEVANCE TO THE CALFED SCIENCE PROGRAM

First, the study will produce water productivity (WP) maps and models for major crops in California that will “pin-point” irrigated cropland areas with low and high WP. These maps and models will provide precise locations from where we can save water and by how much. A summary of the cost-benefit analysis of various crop shifting alternatives will be shown to key stakeholders in water resources management. Second, practical methods and protocols of water and crop productivity mapping, and water use mapping will be established using advanced remotely sensed data (e.g., Hyperion, IKONOS, Quickbird, Rapideye, ALI) and modeling. The calibrated models for crop yield and ET can be backcasted using historical remotely sensed imagery to determine trends in water productivity for California. A spatial representation of these trends would pinpoint “hotspots” across the state where water availability will be severely limited in the future. Third, this research indirectly benefits two other major research areas: climate variability and change and understanding the causes and consequences of ecological change. Evapotranspiration is a key component of the atmospheric water cycle and energy balance. The development of an accurate model of ET would improve the parameterization of climate and hydrologic models. Irrigated farmland in many parts of the world influences regional climate. A map of irrigated farmland combined with a time series of biomass and ET will improve our understanding of terrestrial moisture flux and its influence on California


climate. Biomass is a key input to ecological models. The improvement of model inversion using remote sensing to estimate biomass will assist ecologists’ assessment of ecosystem health and change. Water use and future availability impacts natural ecosystems and these data would benefit ecologists. Fourth, a new vegetation index based approach (as opposed to surface energy balance models) to water use modeling will be demonstrated. This is specifically crucial at a time when thermal sensor is becoming increasingly difficult to get funded—especially at <100m resolution. The key outcome of this sub-group’s work will be: (a) an innovative ET model, (b) establishment of actual water use of crops, and (c) development of scenarios on how and where we can save water. Fifth, crop phenology will help us understand climate change and its impact on water use by crops. Sixth, development of scenarios of future water use on agricultural lands based on the water productivity maps developed by other research team members. The scenario outcomes would identify spatially where we could gain "new water" and the opportunities for restoration. The research will analyze potential reductions in applied water, which allow farmers and water agencies to remove less water from streams, improving stream quality and ecosystem health, while reducing pumping, delivery, and treatment costs. Scenarios would show spatially explicit changes in climatic factors, crop choices, irrigation technologies, irrigation management practices, and crop cultivation practices.

Finally, the study meets the criteria of Calfed’s 2009 PSP Topic 3., Coupled Hydrologic and Ecosystem Models. We will investigate connectivity between agricultural and riparian water use through isotope sampling and build a hydro-eco model that relates riparian water use to primary productivity and litter production of dominant Central Valley riparian plants, a significant component of salmonid food webs. Focusing on the San Joaquin River National Wildlife Refuge, we will demonstrate the ecological consequences and restoration opportunities that increased crop water productivity generates for riparian vegetation, identify where ecosystems may be impacted by reduced return flows, and demonstrate how these ecosystems could be supported with an additional water supply from agricultural return flow savings (possibly up to 30% more water). We will show through improved WP in irrigated croplands, various quanta of “new water” that becomes available for alternative uses like riparian restoration, re-forestation, recreation, and health. Through a partnership with the Refuge, our models can be used to explore the application of riparian water use maps for future riparian restoration planning in the Central Valley, especially under different climate change scenarios.

10. DELIVERABLES AND MILESTONES: THE PROJECT WILL PROVIDE 17 DISTINCT DELIVERABLES AS PER A DEFINED TIME-LINE.

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10.1 Annual Project Reports

Annual reports are planned for delivery on April 30, 2011, April 30, 2012, and April 30, 2013. The final project report will be delivered before April 30, 2013. We will also publish peer-
reviewed journal papers and prepare workshop materials on each component of the project (WP, water use, phenology, riparian productivity, water savings). A custom USGS website with web mapping capabilities will disseminate data-models-maps-products.

11. FEASIBILITY

11.1 Management Plan

There are 7 sub-groups interacting and working as a team. **Sub-group A (project management and water productivity mapping):** Dr. Prasad S. Thenkabail (USGS), PI, will organize meetings, ensure coordination amongst team members, provide intellectual leadership on water productivity (WP) modeling and mapping, and take responsibility for deliverables. He will be supported by **Dr. Wang Dong** (USDA-ARS, California) in crop productivity mapping—especially, bringing knowledge of California crops. The entire team will be supported by 2 post-docs—one on water productivity mapping, remote sensing, and heavy computing and a second person on water use:ET modeling and remote sensing. **Sub-group B: (Water use (ET_{\text{actual}}) modeling):** will be led by **Dr. Pamela Nagler** (USGS-BRD). She will work on evaluating various ET models and coming up with models with least uncertainty. Her main role will be to develop new ET prediction algorithms for five major crops (that constitute 40% of croplands of California) as well as riparian vegetation. The VI based ET model proposed here are innovative and will be compared with widely used SEBAL, METRIC, and SSEB models. **Sub-group C: (hyperspectral remote sensing and uncertainties-errors-accuracies):** Dr. Terrence Slonecker (USGS) will look into advances one can make in WP studies using hyperspectral indices relative to broad band indices. Dr. Slonecker will also establish the accuracies, errors, and uncertainties in WP models and maps when using hyperspectral, hyperspatial, and advanced multispectral data. Dr. Slonecker will be supported by a graduate student (University of Maryland-USGS) in advanced remote sensing. **Sub-group D: (Phenology):** Dr. Cynthia Wallace (USGS) has extensive experience working with multi-temporal data sets, including AVHRR and MODIS, to extract pheno-metrics for habitat mapping and resource management applications. She will lead the effort in developing algorithms for phenological characterization of crops and riparian vegetation. She will be assisted by a graduate student (University of Arizona). **Sub-group F (scenarios for new water plus climate-water availability-water use):** This sub-group, lead by the Pacific Institute (California) Dr. Peter H. Gleick (Pacific Institute), Dr. Juliet Christian-Smith (Pacific Institute), and Ms. Heather Cooley (Pacific Institute) will: (a) provide various scenarios of water to better understand the consequences of choices or policies on a wide range of plausible future conditions; (b) simulate “new water” saved through various scenarios such as: (i) improved WP and (ii) re-allocation of crops (e.g., growing wheat instead of rice); and (c) identify spatially where we could gain "new water" and the opportunities for restoration based on climate projections. **Sub-group E and G: (Riparian productivity modeling and restoration planning):** Dr. Kristin Byrd (USGS) will lead the hydro-eco riparian productivity modeling effort and will be supported by **Dr. Alex Finkral** (Northern Arizona University). They will be assisted by a graduate student (Stanford University-USGS) on ecology. They will collaborate with Eric Hopson (San Joaquin River National Wildlife Refuge, CA) for applying research results to riparian restoration planning and future water requirements of restored riparian vegetation under various climate change scenarios.
11.2 Qualifications

**Sub-group A (water productivity models and maps)**: 1a. Dr. Prasad S. Thenkabail, PI, Research Geographer-14, US Geological Survey, Tel.: 928-556-7221, Email: pthenkabail@usgs.gov. 1b. Post-doc 1 on water productivity modeling and mapping and advanced remote sensing; 1c. Post-doc 2 on water productivity modeling and mapping and advanced remote sensing; Roles and responsibilities: project management and leadership and water productivity mapping and modeling. **Sub-group B (water use and ET modeling)**: 2a. Dr. Pamela Nagler, Research Physical Scientist, USGS Southwest Biological Science Center, Tel.:520-621-1472; Email: pnagler@usgs.gov. Roles and responsibilities: ET (water use) modeling of croplands and riparian vegetation. **Sub-group C (phenology)**: 3a. Dr. Cynthia Wallace, Research Geographer, USGS Southwest Geographic Science Team, (520) 670-5589. Email: cwallace@usgs.gov 3b. Graduate student on phenology-climate (University of Arizona). Roles and responsibilities: Phenometrics of croplands and riparian vegetation. **Sub-group D (hyperspectral remote sensing, uncertainty analysis in WP mapping)**: 4a. Dr. E. Terrence Slonecker, Research Geographer, U.S. Geological Survey, Eastern Geographic Science Center, Tel.: 703-648-4289, Email: tslonecker@usgs.gov. Graduate student (University of Maryland\USGS). 4b. Graduate student on advanced remote sensing (USGS). Roles and responsibilities: advances in WP mapping using remote sensing, uncertainty-error-accuracy analysis of WP mapping using remote sensing at various resolutions. **Sub-group E (riparian productivity modeling)**: 5a. Dr. Kristin B. Byrd, Physical Scientist, USGS, Tel.:650-329-4279; Email: kbyrd@usgs.gov. 5b. Prof. Alex Finkral, Assistant Professor of Forestry, Northern Arizona University (NAU), Flagstaff. Tel.: 928-523-1378, Email: alex.finkral@nau.edu. 5c. Graduate student on ecology (Stanford University\USGS). Roles and responsibilities: riparian productivity modeling. **Sub-group F (scenario analysis)**. Dr. Peter H. Gleick (Pacific Institute), President, Pacific Institute, Tel.: 510-251-1600. Email: pgleick@pipeline.com. Roles and responsibilities: project advisor, scenario analysis. Dr. Juliet Christian-Smith (Pacific Institute), Senior Research Associate, Pacific Institute, Tel.: 510-251-1600. Email: jchristiansmith@pacinst.org. Roles and responsibilities: scenario analysis, climate-water availability-water use. Ms. Heather Cooley, Research Associate, Pacific Institute, Tel.: 510-251-1600. Email: jchristiansmith@pacinst.org. Roles and responsibilities: scenario analysis, climate-water availability-water use. **Sub-group G (conservation/end user)**: i. Eric Hopson (San Joaquin River National Wildlife Refuge, CA). Roles and responsibilities: use of research methods-models-data-products, evaluate performance, and provide feedback.

11.3 Facilities/Equipment/Study Area

The USGS, Flagstaff and Menlo Park offices have excellent remote sensing hardware, software, and expertise. There are several PC workstations + 20 TB of storage space. Software includes several licenses for Earth Resource Mapper (ERMapper 8.2), ERDAS Imagine 9.2, ArcGIS 9.3 and ArcGIS Server 9.3, IDL and ENVI. Other equipment includes an ASD spectroradiometer, GPS receivers, and SAS statistical software. **Field equipment**: AccuPAR LP-80 ceptometer, ASD spectroradiometer (400-2500 nm), GPS, ET$_a$ measurement apparatus (existing Bowen ratio towers, lysimeters, scintillometer).

12. BUDGET

Total budget: $1,884,508 (over 3 years). Year 1: $643,551, Year 2: $624,184, and Year 3: $616,773. The budget includes salaries of senior researchers, post docs, graduate students, travel, and field campaigns.
13. REFERENCES


Appendix III

Letters of Support

December 4, 2009

Dr. Prasad S. Thenkabail
N. Gemini Dr.
Flagstaff, AZ 86001

Dear Dr. Thenkabail,

For over two decades, the Pacific Institute has been calling for better water use measurement in the state of California. An accurate accounting of water use, particularly in the agricultural sector which uses approximately 80% of our developed water supply, is critical in order to manage our water resources sustainably. As the state confronts what could be a fourth dry year, accurate water use measurement has never been more urgent. Thus, I strongly support the proposal Predicting and Preventing Crisis in Irrigated Water Use in a Changing Climate—Measuring, Modeling and Mapping Trends and Changes in Agricultural Water Productivity for California.

This research would tackle two of the greatest unknowns in terms of our current understanding of agricultural water use—the first being actual (rather than modeled) crop water use estimates, and the second being actual applied water estimates (from field work and turnout meters at the farm scale, rather than self-reported data at the irrigation district scale). These data will allow us to develop an extremely precise, and spatially explicit, understanding of crop water use and agricultural return flows—and to compare the results with other statewide water planning efforts (including modeled crop evapo-transpiration rates from CIMIS and estimated agricultural water use from the Department of Water Resources’ Water Plan).

This is an extremely important and timely research proposal, and therefore I give it my highest recommendation.

Sincerely,

[Signature]

Dr. Peter H. Gleick
President, Pacific Institute [22 Years of Research for People and the Planet: 1987-2009]
Member, U.S. National Academy of Sciences
MacArthur Fellow

654 13th Street, Preservation Park, Oakland, California 94612, U.S.A.
510-251-1800 | www.pacinst.org
Dr. Prasad S Thenkabail, PhD
Research Geographer – 14
U.S. Geological Survey
USGS Southwest Geographic Science Team
2255 N. Gemini Dr.
Flagstaff, AZ 86001

Dear Dr. Thenkabail,

Thank you for discussing your draft proposal entitled: “Predicting and Preventing Crisis in Irrigated Water Use in a Changing climate: Measuring, Modeling and Mapping Trends and Changes in Agricultural Water Productivity for California.” The San Luis National Wildlife Refuge Complex is interested in research which provides information for enhanced planning and implementation riparian restoration (re-forestation) projects. Specifically, it is thought that this work would be of benefit to ongoing riparian restoration taking place on the San Joaquin River National Wildlife Refuge.

We would be most interested in research which provides answers to the following questions:

1. What is the current water use (evapotranspiration rate) of riparian vegetation by tree species and age class?
2. To what extent does riparian vegetation receives return flows from irrigated croplands?
3. What will be the future water requirements of restored riparian vegetation under different climate change scenarios?
4. To what extent does existing and restored riparian vegetation benefit the life cycle of juvenile and adult anadromous fish species on the lower San Joaquin River.

We look forward to further discussions and planning for your research work on Refuge lands as your project nears implementation.

Sincerely,

Kim Forrest
Wildlife Refuge Manager
December 7, 2009

RE: Proposal Support Letter

To Whom It May Concern:

I am writing in strong support of a proposal entitled: "Predicting and Preventing Crisis in Irrigated Water Use in a Changing Climate: Measuring, Modeling and Mapping Trends and Changes in Agricultural Water Productivity for California" by Prasad Thenkabail and others at USGS, Flagstaff, AZ.

The proposal takes on an approach of quantifying potential water savings or “new water” by identifying “low” and “high” areas of water use efficiency or “water productivity” of various cropping systems in central California. The logic is that if water use in the “low” water productivity areas can be improved, less water will be needed in those areas, then additional water may be made available for other purposes. The overall idea matches well with the research missions of the Water Management Research Unit at our USDA ARS Parlier location. Some of our ongoing research projects would also complement the proposed effort or vice versa.

As a research scientist myself with background in remote sensing for water use applications, I am also highly interested in facilitating any potential imagery or ground-truth assessments as needed by the proposed project.

Please contact me if additional information is needed.

Sincerely,

[Signature]

Dong Wang, Ph.D.
Research Leader

Pacific West Area – San Joaquin Valley Agricultural Sciences Center
Water Management Research Unit
9611 S. Riverbend Ave., Parlier, CA 93648
Voice: 559.596.2852; Fax: 559.596.2851; E-mail: dong.wang@ars.usda.gov

Agricultural Research - Investing in Your Future
Dear Prasad,

This letter is to show my strongest support for the proposal to quantify agricultural water use in California. My lead role is to provide estimates of agricultural and riparian and upland plant evapotranspiration. Our team will be able to use these estimates to determine where and how much water can be salvaged, particularly given a warming climate. With a student who will apply my riparian and crop coefficient models to give an accurate new estimate of plant water use, we will be able to supply current water use for five main crops and surrounding natural vegetation and predict how these estimates will change in a hotter climate. My team will then assess how the changes in available water and salvaged water will affect species that rely on that ecological water supply. The proposal is of importance and interest because in the west, with drought and population growth, water is more important than gold. Quantifying where and how much we can save water is critical to support future wildlife and habitat.

Pamela Nagler, Ph.D.
Research Physical Scientist
December 7, 2009

Dr. Prasad S. Thenkabail  
U. S. Geological Survey  
USGS Southwest Geographic Science Team  
2255 N. Gemini Dr.  
Flagstaff, AZ 86001

Dear Dr. Thenkabail,

The purpose of this letter is to confirm my role as co-Investigator of the proposal entitled "Predicting and Preventing Crisis in Irrigated Water Use in a Changing Climate: Measuring, Modeling and Mapping Trends and Changes in Agricultural Water Productivity for California", submitted to the CALFED Science Program. My role will be to lead the Riparian Ecology sub-group. I look forward to contributing my expertise in California riparian systems to this study of agricultural and riparian water use.

Riparian plant species in the Salicaceae family (willows, poplars, cottonwood) require coordination between seed release timing and peak spring runoff for seedling establishment. However willows and poplars require perennial water sources to survive. Presently the interspersion of riparian corridors within the matrix of irrigated cropland in California creates conditions for hydrological connectivity from cropland to riparian areas and potential riparian dependencies on groundwater recharge from irrigation return flows.

My contribution to this project will be to develop a hydrological-ecological model of riparian productivity with multiple data products. This model will relate discharge of agricultural drainage water to riparian productivity and production of plant litter and detritus, a key component of juvenile salmonid food webs. To understand hydrological connections between cropland and dominant riparian vegetation, I will identify riparian water sources (stream vs. groundwater) in key areas through stable isotope sampling.

We will further demonstrate the ecological consequences and restoration opportunities that increased crop water productivity generates for riparian vegetation. We will analyze alternative scenarios of water use and productivity in agricultural systems to assess potential implications for existing riparian areas. Through a partnership with the San Joaquin River National Wildlife Refuge, we will explore the application of riparian water use maps for future riparian restoration planning in the Central Valley, given a warming climate. The refuge contains one of California’s largest riparian restoration projects partially irrigated with agricultural drainage water.

Sincerely,

Kristin Byrd, Ph.D., Physical Scientist  
Western Geographic Science Center  
U.S. Geological Survey
November 18, 2009

Dr. Prasad Thenkabail
U. S. Geological Survey
USGS Southwest Geographic Science Team
2255 N. Gemini Dr.
Flagstaff, AZ 86001

Dear Dr. Thenkabail,

The purpose of this letter is to confirm my role as co-Investigator of the proposal entitled "Predicting and Preventing Crisis in Irrigated Water Use in a Changing Climate: Measuring, Modeling and Mapping Trends and Changes in Agricultural Water Productivity for California" submitted to CALFED for the 2010-2013 funding period.

This proposed research is important on many levels: for sustainable water resource management, for conservation efforts, for mitigating the potential effects of global climate change, and others. In riparian areas specifically, changing quantities and qualities of water available will affect flora and fauna species abundance and diversity in ways that may threaten the stability of the system and it will be important to anticipate and manage such changes.

I look forward to working with Dr. Byrd and others in the Ecological Restoration component of the study to map and classify riparian vegetation in California through a water use efficiency lens.

Sincerely,

[Signature]

Alex Finkal, Ph.D.
November 19, 2009

Dr. Prasad Thenkabail
Research Geographer
USGS Southwest Science Center
2255 North Gemini Drive
Flagstaff, Arizona 86001


Dr. Thenkabail:

This letter serves to confirm my support and commitment of resources to your CalFed proposal: "Predicting and Preventing Crisis in Irrigated Water Use in a Changing Climate: Measuring, Modeling and Mapping Trends and Changes in Agricultural Water Productivity for California". Water availability and food security are two of the most fundamental global concerns under emerging climate change scenarios and developing a better understanding of the dynamics of the changing parameters of water and agriculture, especially on a regional scale, is central to managing future changes and predicting destabilizing changes in food security.

I will be happy to lead the sub-group on remote sensing research components of this proposal: the multi-scale utilization of hyperspectral and hyperspatial data, and the possible development of new vegetation indices relating to evapotranspiration, species-specific crop identification and changing water availability/phenology scenarios in a changing climate are an exciting and valuable component of this effort. These efforts will also help other sub-groups and will help achieve the overarching project goals. In these efforts, I will be supported by a graduate student.

I look forward to working with you and the excellent team of researchers that you have assembled for this effort.

Sincerely,

E. Terrence Slonecker, PhD
Research Geographer
Eastern Geographic Science Center
U.S. Geological Survey
November 25, 2009  
Dr. Prasad Thenkabail  
U. S. Geological Survey  
USGS Southwest Geographic Science Team  
2255 N. Gemini Dr.  
Flagstaff, AZ 86001  

Dear Dr. Thenkabail,

The purpose of this letter is to confirm my role as lead co-Investigator for the phenology analysis of the proposal entitled “Predicting and Preventing Crisis in Irrigated Water Use in a Changing climate: Measuring, Modeling and Mapping Trends and Changes in Agricultural Water Productivity for California” to be submitted to the CALFED Science Program.

I look forward to working with you and Dr. Dheeravath to evaluate the relationships between crop type and crop phenology for regional mapping, and to establish relationships between crop phenology of managed landscapes, the vegetation phenology of adjacent riparian ecosystems, and their water use patterns. To effectively manage both of these critical landscapes, especially in a changing climate, it is essential to understand the relationships between their competing water needs, including the amount of water that is sufficient as well as its optimal timing.

The team you have assembled is top-notch and I look forward to a fruitful collaboration. It is exciting to be able to provide strong and practical science to address the important need to optimally manage our agricultural lands while providing water for human population needs and preserving critical ecosystems. Thank you for taking the lead on this important research project.

Sincerely,

Cynthia S.A. Wallace, Ph.D.  
Research Geographer
Dr. Prasad S. Thenkabail  
Research Geographer  
United States Geological Survey  
Flagstaff, AZ 86001

Dear Dr. Thenkabail,

This note is to confirm that the Analytical Spectral Devices (ASD) FieldSpec®3 field spectrometer owned by the Astrogeology Science Center is available for your use in California and/or in the laboratory as part of your proposal submitted to the USGS National Climate Change and Wildlife Science Center (CALSEED) entitled "Predicting and Preventing Crisis in Irrigated Water Use in a Changing Climate: Measuring, Modeling and Mapping Trends and Changes in Agricultural Water Productivity for California." We will provide you information on scheduled availability of the instrument and with training on use and care of the instrument prior to field or lab work. You shall assume responsibility for all damages and repairs to the instrument during any field excursions.

Sincerely,

Jeffrey R. Johnson  
Astrogeology Science Center Director  
U.S. Geological Survey
Appendix IV

CVs of Main Investigators

Curriculum Vitae of Prasad S. Thenkabail
Member, Landsat Science Team (2007-2011)

1.0 Education
1992 Ph.D. Agricultural Engineering (remote sensing: dissertation and specialization), Ohio State University (USA).
1984 M.E. Hydraulics and Water Resources Engineering, Mysore University (India).
1981 Civil Engineering, Mysore University (India).

2.0 Country Work experience:

East Asia: China;
Middle East: Israel, Syria;
North America: United States;
Central Asia: Uzbekistan;
South Asia: Bangladesh, India, Myanmar, Nepal, and Sri Lanka;
Southern Africa: Mozambique, South Africa

3.0 Professional Experience [starting with current]

October, 2008- present
Research Geographer-14, SouthWest Geographic Science Center, U.S. Geological Survey (USGS), Flagstaff, Arizona, USA.

March 2003- September, 2008
(a) Principal Researcher, Global Research Division, (b) Head of Remote Sensing and GIS, (c) Group head, Global research division, and (d) Project leader, Global Irrigated Area Mapping, International Water Management Institute (IWMI), Colombo, Sri Lanka

April 1997- March, 2003
Associate Research Scientist (remote sensing), Yale Center for Earth Observation, (YCEO), Yale University, USA.

Nov. 1995- May 2006

Remote Sensing Specialist, International Institute of Tropical Agriculture (IITA), Nigeria.

Sep. 1988-June 1992
Graduate Research Associate and Ph.D. candidate, Ohio State University, USA

Dec. 1986-June 1988
Scientist, Department of Space, Government of India, National Remote Sensing Agency (NRSA), India.

Lecturer in hydrology, hydraulics, open channel flow. Mysore and Bangalore University (India). Affiliated colleges, India.

4.0 Awards, Reorganization, and Affiliations [starting with most recent]

2008 2006-current
2006 John I. Davidson ASPRS President’s Award for Practical papers
2006 Best paper (1 in 5) each year during the Annual Research Meeting of IWMI.
2006 Best Team, Global Irrigated Area Mapping (GIAM) team.
2004 Member, Landsat Science Team. Selected based on the proposal competition.
2003 Best paper (1 in 5) each year during the Annual Research Meeting of IWMI.
2001 Member, Scientific Advisory Board, RapidEye(satellites, remote sensing, and agriculture). Germany.
2001 Autometric Award for outstanding publication for year 2004; American Society for Photogrammetry and Remote Sensing.

5.0 News maker profiles (samples)
1. People of Landsat in the NASA GSFC web page (2007):
3. ESRI Special achievement in GIS (SAG) award winners (2007):
http://www.watermonitoringalliance.net/index.php?id=355

6.0 Editorial Board of peer-review Journals
- Remote Sensing of Environment, Editorial team
- Journal of Spatial Hydrology, Associate Editor-in-Chief

7.0 Reviewer of peer-review Journal Articles
8.0 Web/Data portals released


9.0 Publications (14 publications listed below; Total number of publications: 60+).

**Book**


**Peer-reviewed papers**


**Thenkabail, P.S., Gangadhararao P., Biggs, T., Krishna, M., and Turrall, H. 2007. Spectral Mapping Techniques to Determine Historical Land use/Land cover (LULC) and Irrigated Areas using Time-series AVHRR Pathfinder Datasets in the Krishna River Basin, India. Photogrammetric Engineering and Remote Sensing. 73(9): 1029-1040. (ASPRS President award for Practical Papers, second place).**


PAMELA L. NAGLER
Research Physical Scientist, Remote Sensing Specialist
U.S. GEOLOGICAL SURVEY, SOUTHWEST BIOLOGICAL SCIENCE CENTER, SONORAN DESERT RESEARCH STATION
University of Arizona, 1110 E. South Campus Drive, Room 131, Tucson, AZ, 85721
Tel. 520-621-1174; Cell. 520-975-3814, Fax 520-670-5001, pnagler@uaga.gov

RESEARCH INTERESTS
Remote sensing (RS) and geo-spatio-temporal applications, biogeography, land cover / land use change (LCLUC) analyses, landscape ecology, riparian and phreatophyte ecosystems, plant stress and water balance, empirical modeling for agricultural and natural decision support systems (DSS), environmental monitoring and assessment for natural resource conservation and management

SELECTED RECENT PUBLICATIONS

PEER-REVIEWED PUBLICATIONS PRODUCED IN FY2010 (n = 7)


PEER-REVIEWED PUBLICATIONS PRODUCED IN FY2009 (n = 8)


EDUCATION

PhD  University of California, Berkeley, 2005
    Environmental Science, Policy, and Management (ESPM)
    Maggi Kelly (chair), Adina Merenlender, Alex Horne, dissertation committee

MA  San Francisco State University, 1998
    Ecology and Systematics

BS  Cornell University, College of Agriculture and Life Sciences, 1993
    Environmental Science

Research Interests: Dr. Byrd has developed and managed research and published in the areas of remote sensing of Pacific Coast wetland and riparian ecosystems, remote sensing applications for restoration planning, wetland sedimentation and soils, and forest soil ecology. With dual expertise in remote sensing and plant ecology she has developed methods for wetland and riparian vegetation mapping and researched effects of soil biological and physical properties on wetland plant distribution and forest regeneration. Dr. Byrd's main interest is in advancing remote sensing capabilities for quantifying productivity to support regional land use planning.

PROFESSIONAL EXPERIENCE

Western Geographic Science Center, Menlo Park, CA


    P.I. Adina Merenlender, in partnership with The Nature Conservancy

Wetlands Bio-Technician, Point Reyes National Seashore, CA (summer position)  May 2001 – Sept. 2001

Senior Staff Biologist, URS Corporation, Oakland, CA  April 1998 – March 2001

    Natural Resources Division, Addis Ababa, Ethiopia

Natural Resources Interpreter, Yosemite National Park, CA (internship)  June 1994 – Sept. 1994


PUBLICATIONS


CONFERENCE PROCEEDINGS


AWARDS, GRANTS AND FELLOWSHIPS

- Estuarine Conservation Research Award 2004
  Elkhorn Slough National Estuarine Research Reserve and the Elkhorn Slough Foundation
- U.C. Center for Water Resources Grant, with P.I. N. Maggi Kelly 2002 – 2004
  Linking upland landcover change with wetland structure in Elkhorn Slough, CA; $56,000
- U.C. Marine Council Coastal Environmental Quality Graduate Fellowship 2002
  Agriculture in the watershed and its impact on the structure of salt marshes in Elkhorn Slough – use of remote sensing for historical change detection; $25,000
  Agriculture in the watershed and its impact on the structure of salt marshes in Elkhorn Slough – use of remote sensing for historical change detection; $17,500
- U.S. Dept. of Education Graduate Assistance in Areas of National Need Fellowship 1995 – 1997
  Support for M.A. at San Francisco State University
  Support for position at the United Nations Economic Commission for Africa, Addis Ababa, Ethiopia
- Yosemite Association Scholarship, Yosemite National Park, CA 1994

TEACHING AND OUTREACH

Introduction to Environmental Science, Graduate Student Instructor Spring 2002, 2004
Environmental Science Department, U.C. Berkeley

Urban Environmental Education, Graduate Student Instructor Spring 2003
ESPM Department, U.C. Berkeley

Environmental Outreach Workshop Leader 2003 – 2005
Environmental Leadership Outreach Program, U.C. Berkeley

Created and led the following environmental science workshops for Bay Area 6 – 12 grade students:
- Protecting the SF Bay and Delta: from regional debates to local action; EarthTeam Network, Berkeley, CA
- WebGIS; Pre-College Academy, U.C. Berkeley
- GPS and Wetlands workshop; Girls, Incorporated, San Leandro, CA
- Kayak Tour of Elkhorn Slough; Global Environment Theme House, U.C. Berkeley

Introductory Botany, Teaching Associate Fall 1996, Spring 1997
Biology Department, San Francisco State University

SERVICE, TRAINING AND SKILLS

Referee for Wetlands, Environmental Management, Environmental Monitoring and Assessment

Skills in: ERDAS Imagine 9.1, Definiens Ecognition 5.0, ArcGIS 9.3, Adobe Photoshop, R, SAS, Stata, Trimble GPS, wetland delineation, plant taxonomy, topographical surveying, photography, proficient in French
ALEX J. FINKRAL
School of Forestry, Northern Arizona University
Flagstaff, AZ 86001

EDUCATION:
2005    Yale University, School of Forestry and Environmental Studies.
        Ph.D. in Silviculture (The Effects of Highgrading on Forest Stands of
        Southern New England).
1997    Yale University, School of Forestry and Environmental Studies.
        M.F. in Silviculture
1992    Colorado State University, College of Natural Resources.
        B.S. in Natural Resource Management.

COUNTRY WORK EXPERIENCE:
North America: U.S., Canada
Europe: Bosnia-Herzegovina, Turkey
Central and South America: Honduras, Panama, Peru
South Asia: Sri Lanka
Africa: Gabon, Republic of Congo, Central African Republic

PROFESSIONAL CAREER:
2005 - present    Assistant Professor of Forest Management. Northern Arizona
                  University, School of Forestry.
1996 – 2005        Manager, School Forests, Yale University School of Forestry and
                  Environmental Studies.
2000                Director (Interim), School Forests, Yale University School of
                  Forestry and Environmental Studies.

CONSULTANCIES:
2008 – Ongoing      Consultant, Beyond Forestry, San Pedro Sula, Honduras. Short
                    rotation teak growth in intensively managed plantations.
1999 - Ongoing      Consultant, Masswood Foresters, L.L.C., Sandisfield, MA and
                    Flagstaff, AZ, USA. Inventory design and implementation,
                    management plans, timber sale marking and administration,
                    development of conservation easements for private landowners
                    and public agencies.
2007-2008            Consultant, Training for Biodiversity Monitoring and Assessment
                    in the Black Sea Region Forests (Mačka, Turkey).
                    Developed materials for and helped teach course for Turkish
                    government foresters.
1997                Consultant, Bosnian Forest Reconnaissance Project, Bosnia-
                    Herzegovina. Inventoried forest stands using qualitative and
                    quantitative methods and assessed forest health. Project supported
                    by U.S. Department of Defense; University of Alaska, Fairbanks;
                    and the World Bank.
SELECTION PUBLICATIONS:


SELECTED GRANTS:


PETER HENRY GLEICK
(July 2007)
Pacific Institute for Studies in Development, Environment, and Security
654 13th Street, Preservation Park, Oakland, California 94612
510 251-1600; 510 251-2203 (telefax); pgleick@pipeline.com

EDUCATION
Doctorate (PhD) University of California, Berkeley, Energy and Resources, 1986.
Master of Science (MS) University of California, Berkeley, Energy and Resources, 1980.
Bachelor of Science (BS) Yale University, in Engineering and Applied Science, 1978. Cum laude, with distinction.

EMPLOYMENT and RESEARCH POSITIONS
President and Co-Founder, 1987 to Present

Research Associate, 1983 to 1986.
Energy and Resources Group, University of California, Berkeley,

Deputy Assistant to the Governor of California. 1980-1982.
Energy and Environment Office of the Governor of California.

Research and Teaching Associate. 1978 to 1981.
University of California and Lawrence Berkeley Laboratory.

HONORS, AWARDS, FELLOWSHIPS
- Named AAAS Fellow (Atmospheric and Hydrospheric Sciences): October 2005 (American Association for the Advancement of Science).
- Elected member of AAAS Atmospheric and Hydrospheric Sciences Section: February 2007-2011.
- Appointed United Nations-Sigma Xi Scientific Expert Group on Climate Change and Sustainable Development. November 2004
- Named MacArthur Fellow. October 2003
- Elected to Phi Beta Delta: Honor Society for scholarly achievement in international education. April 2003
- Named San Francisco Chronicle, one of "90 People to Watch in the '90s." 1990.

PUBLIC AND PROFESSIONAL SERVICE
• Appointed to the Climate Advisory Group of the California Academy of Sciences, 2007-
• Appointed to State of California Climate Change Technical Advisory Group, 2007-
• Elected member: AAAS Atmospheric and Hydrospheric Sciences Section: February 2007-2011
• Vice Chair, American Geophysical Union Global Environmental Change Focus Group, 2006-2008
• Advisory Committee: Rethinking Water Policy Opportunities in California, UCSB/Rand Research, 2005-2006.
• Editorial Board, Annual Reviews of Energy and the Environment, 2001-2004
• Editorial Board, Climatic Change, 1990-present.
• Editorial Board, Water Policy, 1997-present
• 1990 Water Task Group, Second World Climate Conference, Geneva, Switzerland.
• Advisory Committee: Climate Institute's Environmental Refugee Program, 1993-1995.
• Climate and Water Panel, American Association for the Advancement of Science, 1986-1990.
• Committee on Science & International Security, American Association for the Advancement of Science, 1993-95.
• Editorial Board: Global Change and Human Health, 1999-2003
• Interim Board of Directors: Middle East Water Information Network, 1994-1996
• Scientific Review Group, President's Council on Sustainable Development, 1994-1996.
• Surface Water Committee, American Geophysical Union, 1992-1993.

A full publications list is available upon request.
Curriculum Vitae

Dong Wang

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EDUCATION

Ph.D. 1993 University of Wisconsin - Madison Soil & Environ. Physics
M.S. 1989 University of Idaho Irrigation and Drainage
B.S. 1984 Beijing Agricultural Engineering Univ. Irrig and Hydraulic Eng

EMPLOYMENT AND SCIENTIFIC EXPERIENCE

2007 - Present, Research Leader and Soil Scientist, USDA-ARS-SJVASC, Parlier, CA
2000 - 2007, Assistant, Associate with Tenure, Professor, University of Minnesota – Twin Cities
1997 - 2000, Soil Scientist, USDA-ARS US Salinity Laboratory, Riverside, CA

RELEVANT JOURNAL ARTICLES

BIOGRAPHICAL SKETCH
CYNTHIA S.A. WALLACE

EDUCATION
- PhD in Geography, University of Arizona-Tucson, 2002
- MA in Geography, University of Arizona-Tucson, 1997
- MS in Geology, University of Wisconsin-Madison, 1980
- BS in Math and Geology, University of Minnesota-Duluth, 1978, Magna cum Laude

EXPERIENCE
11/04 to present: Research Geographer, U.S. Geological Survey
2/02 to 11/04: Geographer, U.S. Geological Survey
Conduct innovative research for natural resource management applications, especially using remote sensing and spatial analysis technologies; cooperatively identify new areas of interdisciplinary research interest; foster collaborative research efforts; grant, proposal, journal article and report writing; presentations to colleagues and management.
6/95 to 11/02: Research Assistant, Arizona Remote Sensing Center, U. of Arizona
Raster and vector data processing and analysis, primarily for land use and land cover mapping change detection, and landscape trend analysis; generation, interpretation and analysis of data using a variety of image processing, GIS, and statistical software packages; grant, proposal, and report writing; presentations to staff and funding agencies; design and production of graphics.

SELECTED PUBLICATIONS
JULIET CHRISTIAN-SMITH

Pacific Institute
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EDUCATION
2006 Doctorate University of California, Berkeley (Environmental Science, Policy and Management)
2001 Bachelor of Arts Smith College (Biology) cum laude

EMPLOYMENT
May 2008 - present Senior Research Associate, Pacific Institute
Fall 2007 - Spring 2008 Fulbright Fellow to Portugal, U.S. State Department
Summer 2007 Water Management Researcher, University of California Cooperative Extension
January 2006 - May 2007 Lecturer, University of California, Berkeley
May 2005 - Dec 2005 Research Associate, Sierra Institute for Community, Environment

SELECTED HONORS, AWARDS, FELLOWSHIPS
• U.S. Environmental Protection Agency, Environmental Achievement Award (2009)
• Fulbright Fellow (2007-2008)
• Ford Foundation Fellow (2004-2005)
• Sigma Xi Honor Society (2001-present)
• National Science Foundation Undergraduate Research Award (1999)

PUBLIC AND PROFESSIONAL SERVICE
• Water Sub-committee Leader, Climate Adaptation Advisory Panel to the State of California (2009)
• U.S. State Department Invited Speaker, Mission to Canada on Trans-boundary Water Resources (2009)
• Board Member, Agricultural Water Management Council (2009)
• Steering Committee Member, California Agricultural Vision 2030 (2009)

SELECTED RESEARCH PAPERS AND PUBLICATIONS


Heather S. Cooley, M.S.

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EDUCATION

M.S. University of California, Berkeley, Energy and Resources, 2004
B.S. University of California, Berkeley, Molecular Environmental Biology, emphasis in ecology, 1998

PROFESSIONAL EXPERIENCE

Research Associate, November 2004-present
Pacific Institute for Studies in Environment, Development, and Security

Research Associate/Lab Manager, October 2000 to September 2004
Lawrence Berkeley National Laboratory, Berkeley, California

Teaching Assistant, January 2004 to June 2004
University of California, Berkeley, California

Cartographer and Database Assistant, January, 2001 to June 2001
Pesticide Action Network North America, San Francisco, California

Outdoor/Environmental Educator, February 2000 to June 2000
Mountain Trail Outdoor School, Hendersonville, NC

Field/Laboratory Technician, June 1998 to December 1999
University of California, Silver Lab, Berkeley, California and Puerto Rico

Field/Laboratory Assistant, October 1996 to September 1997
University of California, Weston Lab, Berkeley, California

SELECT RESEARCH PAPERS AND PUBLICATIONS


SELECT PRESENTATIONS


SELECT AFFILIATIONS

Water Education Foundation, Water Leaders.
B160-05 Public Advisory Committee alternate
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EDUCATION

M.S. University of California, Berkeley, Energy and Resources, 2004
B.S. University of California, Berkeley, Molecular Environmental Biology, emphasis in ecology, 1998

PROFESSIONAL EXPERIENCE

Research Associate, November 2004-present
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Research Associate/Lab Manager, October 2000 to September 2004
Lawrence Berkeley National Laboratory, Berkeley, California

Teaching Assistant, January 2004 to June 2004
University of California, Berkeley, California

Cartographer and Database Assistant, January, 2001 to June 2001
Pesticide Action Network North America, San Francisco, California

Outdoor/Environmental Educator, February 2000 to June 2000
Mountain Trail Outdoor School, Hendersonville, NC

Field/Laboratory Technician, June 1998 to December 1999
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Field/Laboratory Assistant, October 1996 to September 1997
University of California, Weston Lab, Berkeley, California

SELECT RESEARCH PAPERS AND PUBLICATIONS


SELECT PRESENTATIONS


SELECT AFFILIATIONS

Water Education Foundation, Water Leaders.

B160-05 Public Advisory Committee alternate