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January 7, 2005

California Department of Water Resources
Office of Water Use Efficiency
Attn: Ms. Debra Gonzalez
1416 Ninth Street, Room 338
Sacramento, CA 95814

Dear Ms. Gonzalez:

Letter in Support of Project Entitled
"Improvement in the CIMIS California Statewide Potential Evapotranspiration Maps"
Principal Investigator- Dr. Susan Ustin, UCD

It is our pleasure to forward institutional support and approval of the research project by UCD's Dr. Ustin on the referenced research project to the CA Department of Water Resources under the FINAL 2004 Water Use Efficiency Proposal Solicitation.

Please note that UCD takes exception to some of the provisions and language in the Solicitation. Specifically we call your attention to the following:

Section A-9/ B-9: Paragraph B Reports (Request replacing with GIA 101)
Section A-11/ B-11: Intellectual Property Rights (Request replacing with GIA 101)

Please note that agreements with the above considerations have previously been negotiated with CADWR on behalf of the University of California and agreeable language has been included in current agreements with UC Davis.

Should the Department make an award to the University, we would anticipate negotiating terms that comply with University and federal guidelines as they pertain to the higher learning institutions and retention of intellectual property rights.

Please contact the principal investigator for scientific information. Administrative questions may be directed to me at the above contact information.

Sincerely,

David Ricci
Contracts and Grants Analyst

cc: Dr. Ustin

Project Information Form

Applying for: ☒ Urban ☒ Agricultural

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

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

3. Principal applicant (Organization or affiliation): The Regents of the University of California (University of California, Davis)

4. Project Title: Improvement in CIMIS California Statewide Potential Evapotranspiration Maps

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

Name, title
Mailing address
Telephone
Fax.
E-mail

David Ricci
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Office of the Vice Chancellor for Research
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6. Contact person (if different):

Name, title.

Mailing address.

7. Funds requested (dollar amount): $400,770

(from Table C-1, column III, row p)

8. Applicant funds pledged (dollar amount): $0

(from Table C-1, column II, row p)

9. Total project costs (dollar amount): $400,770

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

10. Is your project locally cost effective?

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

☐ (a) yes

☒ (b) no

(If yes, project is not eligible)

11. Explain why this project is not locally cost effective:

Research proposal

12. Estimated Bay-Delta annual net water savings (reduced irrecoverable losses only, in acre-feet): N/A

(from Table C-5a (row E))

13. Cost/AF of water saved to Bay-Delta: N/A

(from Table C-7 (row L))

14. Cost/AF of water saved with Applicant Contribution: N/A

(from Table C-7 (row N))

15. Duration of project (month/year to month/year): 12/01/05 - 11/30/08

16. State Assembly District where the project is to be conducted: 8th District

17. State Senate District where the project is to be conducted: 5th District

18. Congressional district(s) where the project is to be conducted: 1 (One)

19. County where the project is to be conducted: Yolo

21. How many service connections in your service area (urban)? ______

22. How many acre-feet of water per year does your agency serve? N/A

23. Type of applicant (select one): N/A

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

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

(Provide supporting documentation.)

- ☐ (a) yes, ________ median household income
- ☒ (b) no

2004 Water Use Efficiency Proposal Solicitation Package
APPENDIX B: Signature Page

By signing below, the official declares the following:

The truthfulness of all representations in the proposal;

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

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

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

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

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

Signature	Name and title	Date
[signature]	**David Ricci** **Contracts and Grants Analyst**	1/7/05

Improvement in CIMIS California Statewide Potential Evapotranspiration Maps

Susan Ustin and Quinn Hart
{slustin,qjhart}@ucdavis.edu

January 10, 2005

In 2002-2004, California Space UC Davis Center of Excellance (*CalSpace*) demonstrated the feasibility of creating daily Reference Evapotranspiration (ET_0) maps for California, using satellite and ground station data. The current method provides good estimates of ET_0 and is planned for incorporation into the California Irrigation Management Information System (*CIMIS*) website, providing users access to spatial distributions of ET_0 and expanded report generation facilities. However, potential improvements have been identified with the methodology and the execution of the application.

The goal of this project is to: *1) improve spatially distributed daily ET_0 estimations, 2) produce daily ET_0 maps for the State of California at high spatial resolution, 3) provide statistical reports about the spatial data, and 4) improve the technical robustness of the application.*

ET_0 is a reference evapotranspiration determined by micrometeorological measurements above a reference crop (uniform closely-cropped grass) that is well irrigated and actively growing. The methodology for creating Statewide ET_0 maps includes National Oceanic and Atmospheric Administration (NOAA) Geostationary Operational Environmental Satellite (GOES) data combined with the *CIMIS* and ancillary datasets such as digital elevation maps. ET_0 estimation follows the Penman-Monteith procedures using the GOES satellite data to estimate net radiation. This proposal investigates additional satellite data, like surface temperatures, to further improve other meteorological inputs to the ET_0 model. Data from the MODIS instruments on NASA's two polar orbiting satellites will be explored to see if the final ET_0 product can be improved.

Key Words: agricultural water use, water use monitoring, weather satellite, evapotranspiration, remote sensing, image processing, environmental monitoring, water use technical assistance.

1 Relevance and Importance

Evapotranspiration (ET) combines the loss of water to the atmosphere by evaporation from soil and plant surfaces and transpiration from plant tissues. ET indicates of how much water crops, lawn, garden, and trees need for healthy growth and productivity. ET is an important indicator in both agricultural and urban settings and can be considered a measure of how much water is required for the healthy functioning of a particular plant-soil-atmosphere system. By knowing how much water a particular system needs, a variety of water issues, such as irrigation scheduling and design, landscape planning and water transfer among others, can be addressed.

Many factors affect ET including weather, soil and plant parameters. Estimating ET using analytical and empirical equations is a common practice and most ET equations were developed by correlating measured ET to parameters that directly or indirectly affect ET. Since it is extremely difficult to formulate an equation that can produce estimates of ET under all different sets of conditions, the idea of reference crop evapotranspiration was developed by researchers. Reference Evapotranspiration (ET_0) is the ET rate of a reference crop such as grass or alfalfa. ET from a standardized grass surface is commonly denoted as ET_0.

Using known parameters and measured weather values from weather stations on standardized reference surfaces, ET_0 is estimated. Then, a crop factor, commonly known as crop coefficient (Kc), is used to calculate the actual evapotranspiration (ETc) for a specific crop in the same microclimate as the weather station site.

The highly successful *CIMIS* network was developed by the California Department of Water Resource and the University of California at Davis in 1982, to help farmers, turf managers and other resource managers develop water budgets that would improve irrigation scheduling and limit over-watering. The *CIMIS* system is a repository of meteorological data collected at over 130 computerized weather stations located at key agricultural and municipal sites throughout California which provide comprehensive, timely, weather data collected daily.

2 Technical Merit, Feasibility

Table 1 defines the symbols used in this proposal.

ET_0 is a reference evapotranspiration determined by micrometeorological measurements above a reference crop (uniform closely-cropped grass) that is well irrigated and actively growing. The Penman-Monteith equation is selected as the method that provides the most consistent ET_0 values in all regions and climates and for which the (ET_0) can be unambiguously determined [APRS98].

The Department of Water Resources and UC Davis, have developed a map of ET_0 zones in California[CIM99], shown in Figure 1. The map shows variations in the expected ET_0 due to average temperatures and relative humidity, radiation, wind, and maritime influences. There are 18 separate zones which delineate different regions and influences in California.

Table 1: Symbols used in this report

Symbol	Description	Units
ET_0	Reference Evapotranspiration	$^{mm}/_{day}$
T_m	Daily mean air temperature at 2 m height	°C
T_n	Daily maximum air temperature at 2 m height	°C
T_x	Daily minimum air temperature at 2 m height	°C
T_{dewp}	Dew point temperature at 2 m height	°C
U_2	Wind speed at 2 m height	$^{m}/_{s}$
Rh_{max}	Maximum relative humidity	%
e_a	Actual vapor pressure	kPa
e_s	Saturation vapor pressure	kPa
γ	Psychrometric constant	$^{kPa}/_{°C}$
Δ	Slope vapor pressure curve	$^{kPa}/_{°C}$
R_n	Net radiation	$^{MJ}/_{m^2\,day}$
R_{nl}	Net long wave radiation	$^{MJ}/_{m^2\,day}$
R_s	Solar radiation	$^{MJ}/_{m^2\,day}$
G	Soil heat flux density	$^{MJ}/_{m^2\,day}$

The Penman-Monteith equation, (Eq 1) [APRS98] simulates the control that environmental factors, such as solar radiation, wind speed, air temperature and humidity exert on ET_0. These factors influence, either by providing the energy for vaporization or by helping the removal of water vapor from the surface. For example, solar radiation is typically the main driver for ET_0. Another driving force of evapotranspiration is the difference of water content between the air and the surface; large differences facilitate water removal while a small difference lower ET_0. However as this transfer of water occurs the air surrounding the surface saturates diminishing the rate of evapotranspiration. Here wind speed plays an important role, replacing the saturated air above the evaporating surface and maintaining a water content gradient between the air and surface.

The equation combines a mass transfer approach with an energy balance. The basis for the equation is that evapotranspiration from a surface is proportional to the conductance of the pathway between the surface and the air as well as its water vapor concentration difference. Additionally, the evapotranspiration is constrained by the available energy to evaporate water. The control of environmental factors is expressed through the radiation budget, vapor pressure deficit and water vapor conductance. Even though the behavior of this equation is very complex, generally we can state that an increase in radiant energy or vapor pressure deficit produces an increase in ET_0. Similarly, increases in water vapor conductance also increase the ET_0, but changes in the boundary layer conductance can either increase or decrease ET_0. The Penman-Monteith ET_0 for daily time steps is expressed as:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T_m+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{1}$$

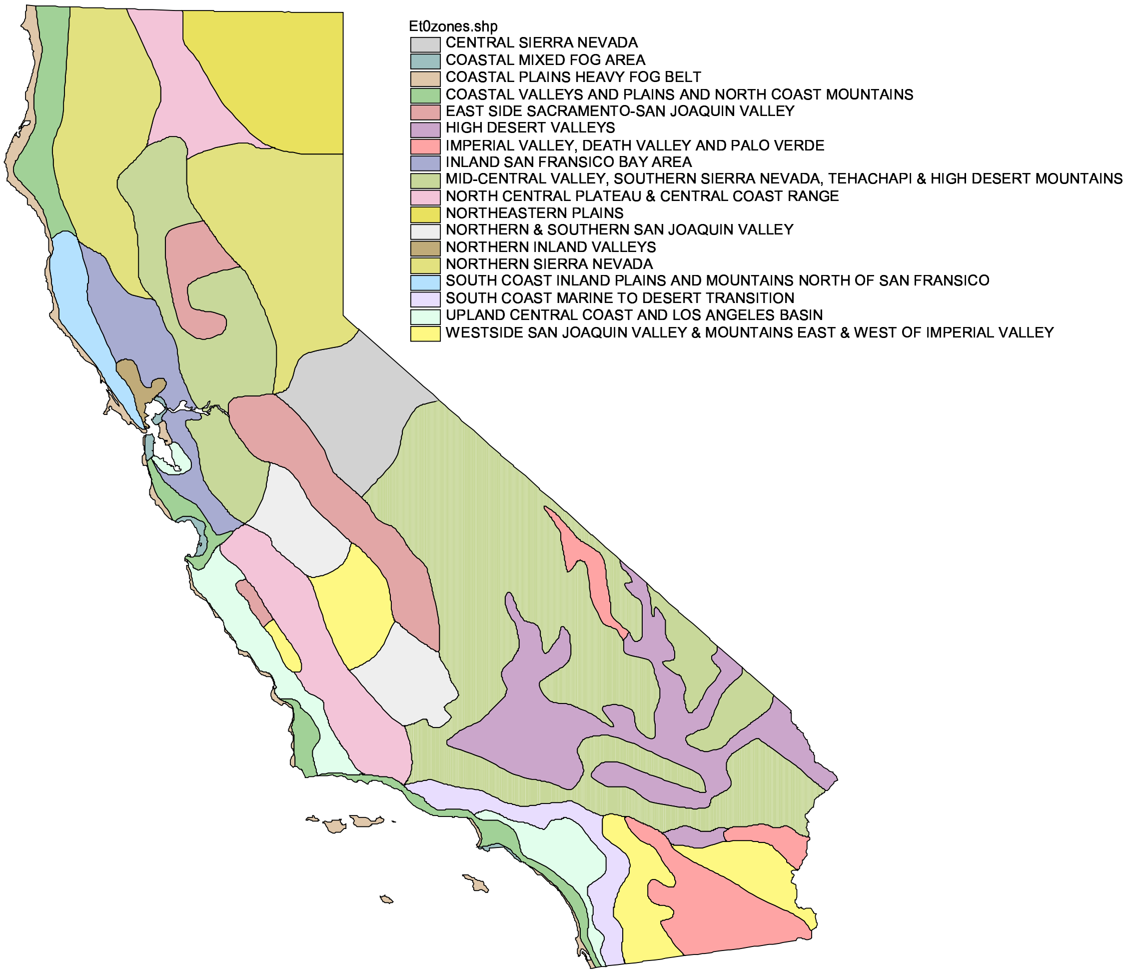


Figure 1: ET_0 zones for California.

Where (R_n-G) represents the supply of energy available to vaporize water. In this case Net radiation (R_n) is the dominant term in the radiation budget, since G is assumed to have a negligible value at a daily time scale. The R_n is calculated as the difference between the incoming Net solar radiation (R_{ns}) and the outgoing Net long wave radiation (R_{nl}). R_{ns} represents a fraction of Solar radiation (R_s). R_s is the amount of incoming solar radiation that reaches the earth surface, after accounting for the effects of absorption, scattering and reflection of the atmosphere. However, not all the R_s that reaches the surface can be used, since a fraction of it is reflected from the earth surface back to the atmosphere. R_{ns} represents the portion of R_s that is not reflected. R_{nl} represents the radiation emitted by the earth and the energy emitted by the atmosphere.

The water content of the air is represented by the vapor pressure. (e_s - e_a) expresses the vapor pressure deficit. The e_s represents the mean water vapor pressure for a day and it is computed as the mean between saturation vapor pressure at maximum temperature and saturation vapor pressure at minimum temperature. The e_a represents the actual vapor pressure and it is calculated as a function of dewpoint temperature. Then these results are averaged. (1+0.34 U_2) represent the aerodynamic and surface resistance. Δ represents the slope vapor pressure curve and gamma the psychrometric constant. T_m refers as the mean temperature.

The model requires inputs of climatic data to characterize the environment where ET_0 is estimated. These data comprise: air temperature,solar radiation at the surface, average daily wind speed and maximum relative humidity or dew point. Solar radiation is currently derived from GOES satellite imagery. Temperature, average wind speed, maximum relative humidity and dew point data are derived from interpolating point data from the network of *CIMIS* weather stations.

2.1 Ground Station Interpolation

Maximum and minimum temperature, average wind speed, maximum relative humidity and dew point temperature are derived by spatially interpolating point data from a network of approximately 130 *CIMIS* weather stations. These weather stations are spatially distributed over the State of California, Figure 2. Most stations are located in agricultural regions and coverage in the mountainous and desert areas of California are sparsely covered.

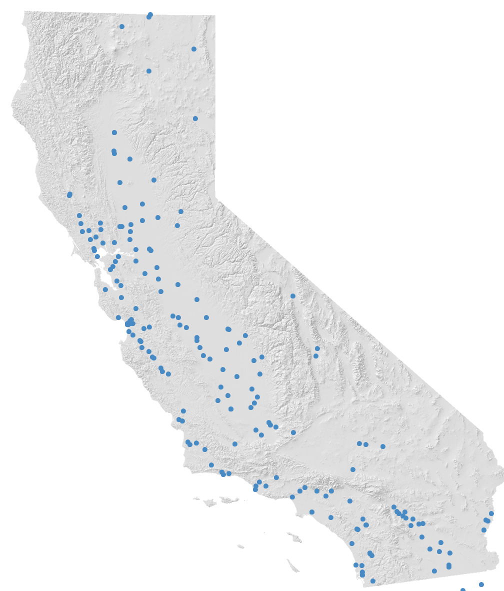


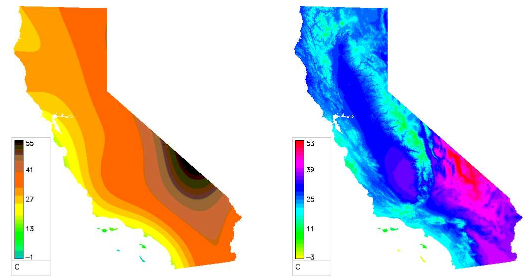
Figure 2: *CIMIS* weather stations

Interpolation of data consists of using a mathematical function to estimate values at locations where no measurements are available. When spatial information (i.e. geographical location) is involved, the interpolation consists of generating surfaces of continuous data from data collected at discrete locations. Even though there are numerous spatial interpolation methods, all of them are built on the assumptions that (1) attributes are continuous over space and (2) values closer together are more likely to be similar than those farther apart.

2.1.1 Temperature

Values of minimum, maximum and dew point temperatures are required to estimate the evapotranspiration. Minimum and maximum temperature are used to compute average temperature, long wave radiation, saturation vapor pressure and the slope vapor pressure curve. Dew point temperature is used to compute actual vapor pressure. The temperature maps in the current version were generated from averaging the results of DayMet [PETW97] and splines interpolation corrected by elevation.

When splines were used in temperature estimations, they were first applied to the data normalized at sea level and then corrected by elevation. Rather than using the elevation variations of the *CIMIS* stations our method relied on lapse rate correction of temperature. Daily temperature measurements from the *CIMIS* stations were normalized to sea level using the lapse rates and a 2D spline, which does not include elevation dependence, was fit to these normalized data. The resulting values were then corrected by lapse rate along with elevation data for the state.



(a) Normalized (b) Elevation Corrected

Figure 3: Interpolated temperature

Figure 3 shows an example temperature calculation using this method. This figure shows a spline interpolation from temperatures normalized to sea level, and the extrapolation after correcting for elevation. This method generally predicts slow changes in the normalized temperature, while maintaining strong elevation dependence of the temperatures.

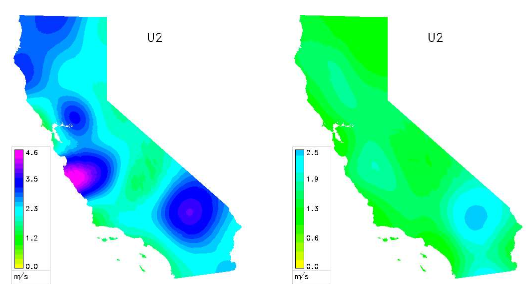
2.1.2 Water Vapor

The actual vapor pressure, in conjunction with saturation vapor pressure, is used to estimate the vapor pressure deficit of the air. This deficit represents the gradient of water vapor between the evaporating surface and the air and constitutes one of the determinant drivers for the aerodynamic component of evapotranspiration. The actual vapor pressure is also used in the estimation of long wave radiation.

-

2.1.3 Wind Speed

Average daily wind speed standardized at 2 m high above the surface is used to compute the aerodynamic resistance, which represents the resistance that air above the vegetative surface imposes over the evapotranspiration. Figure 4 shows some example wind speed interpolations. The figure shows two typical wind speed interpolations, one on a calm day and the other on a windy day.



(a) 2003-06-18 (b) 2003-12-21

Figure 4: Interpolated wind speed

2.2 Solar Radiation Model

The solar radiation model used is the Heliosat-II [RBW00, LAW02]. The Heliosat-II model uses an analytical integration over solar angles as opposed to other models which approximate over instantaneous values. This has a number of advantages. It is possible to change the frequency of GOES cloud cover estimations without modifying the methodology used. Missing cloud cover estimates, caused by lost GOES images, can also be handled by simply extending the intervals around the missing values. The analytical integration assigns proper weights to the remaining cloud cover estimates.

Atmospheric transmission in the Heliosat-II model combines aspects of aerosols, relative humidity, ozone, and molecular scattering into a single parameter, the Linke turbidity which relates the optical depth for an arbitrary atmosphere to an equivalent atmospheric depth of a Rayleigh only scattering atmosphere. Along with the sun's geometry and the elevation, the predicted insolation is calculated with this parameter. Seasonal values of the Linke turbidity are taken from a world database of the turbidity estimations.

2.2.1 Solar Insolation

Inputs to the radiative term of the Penmen-Monteith equation include three energy terms; solar radiation at the surface, long wave radiation, and soil heat flux density which for daily calculations of ET_0 is usually assumed to be zero. Solar radiation can be measured directly, or modeled. Long wave radiation is primarily a function of surface temperature, but is also affected by the daily average cloud cover, which affects the emissivity of the sky.

Solar insolation is linearly related to ET_0, and in many cases is the largest driving factor in its calculation. It is therefore important to measure this parameter accurately. *CIMIS* stations measure solar insolation directly, but it cannot be reliably interpolated spatially, since it is dependant on the daily average cloud cover, which does not interpolate well.

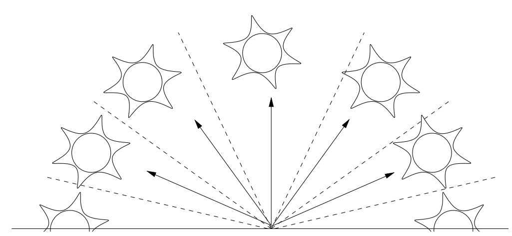


Figure 5: Measurement example

R_s is calculated as a model of clear sky insolation combined with hourly estimates of the cloud cover using GOES visible channel imager data. This method allows an estimation of solar insolation that is independent of any measurements from the *CIMIS* stations. For each location in California, the sunrise, and sunset times are calculated. Within this sunlit period, GOES data are available at hourly intervals, Figure 5. The sun angle for each of these times are shown with solid lines. From each of these hourly GOES images, an estimation of cloud cover is calculated which is assumed constant over the intervals of time/sun angle shown with dotted lines. The Heliosat-II model is used to calculate the clear sky insolation for each of these intervals. The clear sky insolation, and cloud cover factor are used to predict the actual insolation for each interval. Finally, the contributions from all intervals are summed for the daily estimate of solar insolation.

The clear sky insolation is modeled directly. The GOES imager data was used to calculate hourly estimates of cloud cover. This is a relatively simple method which uses an empirical relation that roughly linearly relates a measured cloud brightness with the clear-sky fraction.

This empirical relation has been shown to be valid in a number of studies [BCH96].

Cloud brightness at time i, n_i is defined as

$$n_i = \frac{V_i - \rho_i}{BX_i - \rho_i}$$

where V_i is the visible imager channel value, ρ_i is the surface albedo expressed in visible channel values, and BX_i is the maximum pixel brightness, also expressed in visible channel values. n_i ranges from 0 with no clouds, to 1 with complete cloud cover.

The surface albedo is calculated for each pixel by taking the minimum measured value of V_i over the previous two weeks. The assumption being that at some point in that time frame there were no clouds over that region. The maximum pixel brightness BX_i is calculated by taking the maximum value of *any* pixel in the last two weeks. To avoid single pixel anomalies, this value is taken on a 9x9 average of the visible image. This has the effect of choosing bright pixels that are part of a large clouded region. By using these empirical methods of predicting surface albedo and cloud brightness, many confusing effects can be avoided. For example, differences due to changing solar view angles or seasonal changes in the surface are taken care of by the changing albedo values.

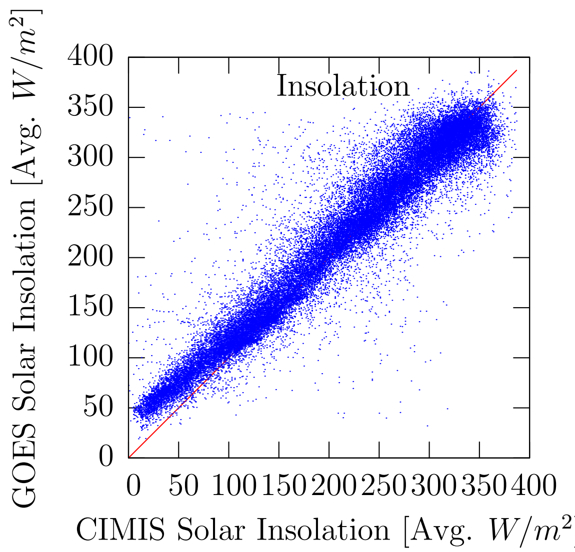


Figure 6: Solar insolation comparison

With hourly estimations of the clear sky factor, K_i, and the modeled clear sky solar insolation G_{ci}, the daily solar insolation is simply the sum of these data

$$G = \sum_i K_i G_{ci}$$

In addition, an estimation of the daily clear sky factor can be made as well. This is used in the calculation of the long wave radiation, to help determine the emissivity of the atmosphere. The daily clear sky factor, K is equal to $K = \frac{G}{G_c}$, where $G_c = \sum_i G_{ci}$.

Figure 6 shows a comparison of the predicted and measured solar insolation at the *CIMIS* stations over the course of one year.

2.2.2 Long Wave Radiation

The daily long wave radiation, R_{nl}, is derived from the Stafan-Boltzman law, with an estimation of the emissivity of the sky based on the water vapor and cloud cover.

$$R_{nl} = -(1.35K - 0.35)(0.34 - 0.14\sqrt{e_a}) \quad (2)$$

$$\sigma\frac{(T_x + 273.16)^4 + (T_n + 273.16)^4}{2} \quad (3)$$

Most of these values are based on interpolated values with the exception of cloud cover.

2.3 Proposed New Tasks to Improve ET_0 Estimates

The temperature, wind speed, and humidity interpolations are limited by the lack of CIMIS stations located in the mountain systems of California. Additionally, the small number of stations in the desert regions east of the Sierra Nevada and Transverse ranges, cause large errors in the interpolation schemes. Greater use of the geostationary GOES weather satellite and/or the polar orbiting Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on the Terra and Aqua satellites could be made by using the Near-Infrared (NIR), Mid-Infrared (MIR) and Thermal Infrared (TIR) images and sounder data to improve the spatial interpolation of the *CIMIS* stations. The following tasks are proposed to be performed under a new contract.

- Improve air temperature and wind speed estimations by adding additional data from GOES-derived surface temperatures.
- Improve atmospheric water content estimations with additional data from GOES water vapor measurements.
- Investigate hourly estimations of ET_0 integrated to daily values, as opposed to daily calculations.

We will develop new tools to improve the usability of the derived ET_0 maps on the *CIMIS* web site, including;

- Provide statistical analysis of daily spatial maps for regional summaries of ET_0 and other parameters.
- Improve the reliability and robustness of the ET_0 application as a whole.

2.3.1 Satellite data based improvements

The previous CIMIS ETo study utilized spatial interpolation schemes to spatialize the CIMIS weather station data over the state. Because the air temperature conditions for CIMIS are standardized at 2m height above a uniform well-watered clipped grass surface, it was considered important in the previous study to explore interpolation schemes that utilized the existing network rather than introduce biases due to including NOAA station data (collected under non-CIMIS conditions) or satellite temperature data, which are considered to measure the surface skin temperature. In the previous study we explored various methods of spatial interpolation developing a combined spline method and DayMet [PETW97]. While this result gave the best overall performance questions remain about how to improve the result, especially in the regions of the state where CIMIS stations are lacking (e.g., the mountain and desert regions). This study will examine utilizing the half-hourly GOES thermal radiance data, calibrated to temperature as a basis to improve the interpolation. The method will calibrate the GOES imagery and then use it to spatially predict this variable for the statewide ETo prediction. We will also explore the use of higher resolution (1km vs. 4km), better calibrated MODIS data, available four times each 24 hour period as a way to improve the temperature prediction. In a longstnding project, MODIS and ASTER at higher spatial resolution multband thermal imagery. are continuously calibrated at Lake Tahoe, Calfiornia by Dr. Simon Hook (JPL) and Dr. Geoff Schladow (UCD). The MODIS instrument can improve the GOES temperature retrieval by cross-calibration or used directly in the ETo interpolation. MODIS thermal bands, along with another thermal imager, ASTER, located on the same platform, are routinely vicariously calibrated based on surface temperature measurements at Lake Tahoe. Thus, the measurements are particularly accurate for the greater California region. These calibration measurements are conducted by Simon Hook (Jet Propulsion Laboratory) and Geoff Schladow (UC Davis) and are available to us for this project. These data are continuously interrigated to determine if predicted temperatures are validated.

It has been shown [MRW+96] that there is a linear relation between surface and air temperature measurements and wind-speed for various land cover type surfaces. Surface temperature measurements derived from additional GOES image channels. These surface temperatures can be used to perturb the interpolated air temperature and wind speed parameters to arrive at estimations in closer agreement with the measured surface temperature. This method requires parameterization of the surface characteristics as well. Since the scale of an individual pixel is on the order 1-2 km^2, many fine scale characteristics are averaged and lost at the coarser scale, and we expect only a small number of unique surface types will be identified that can adequately model the entire state. A MODIS based vegetation type map, a standard product produced on an annual basis (based on a classification scheme that uses the time series to increase accuracy of separation of land cover types) will be investigated as a source for these parameters. Other wind speed models [OO94] will also be investigated for their applicability on a statewide scale.

Dew point temperature at 2 m height (T_{dewp}) is another interpolation that is problematic. Satellite measurements to support water content at the boundary layer will be investigated. Typically, satellite based atmospheric measurements have trouble reaching the surface boundary, but a combined with surface based estimations, may be able to offer adjustments to interpolated-only estimations.

2.3.2 Hourly Estimations

Currently, the standard CIMIS ET_0 calculation is based on daily measurements. This is also the method used in the spatial model. However, it is also possible to estimate ET_0 on hourly time-steps. We will compare integrated estimations of hourly ET_0 to the daily calculations, differences between the two methodologies, and their spatial distribution and causes will be investigated.

2.3.3 Improved ET_0 statistics

Exisiting outputs will be used to include statistics which summarize the results of the spatial parameter estimations. The maps will be summarized daily for each county in California, giving averages, maximum, minimum, and standard deviations, of various parameters including ET_0, R_s,Daily minimum air temperature at 2 m height (T_x), and others. Besides counties, other spatial regions such as zipcodes and water districts will be considered.

To add further robustness to the application we will include better notification of problems in data acquisition and processing; improved error recovery; and automatic inclusion of new CIMIS sites. All code that has been and will be created for this application is GPL copyrighted and are freely available. Furthermore, the application is based entirely on free software packages; such as GRASS for the GIS application, and can be replicated in its entirety.

2.4 Schedule and Project Plan

Year 1 will concentrate on adding the additional statistics capabilities and technical robustness to the exisiting application. This is because these items have been identified as the most important requirements in terms of improving the accessability of the model predictions. In addition, more GOES imager and sounder channels will be included in the database. Deliverables for this year will include: 1) A new application model backend with better error identification and more reliable delivery. 2) Increased on-line capabilities to allow for presentation of new statistics on the spatial data and 3) Documentation of the exisiting software application so that if required, the application can be moved to a more permanent California state location.

Year 2 will concentrate on the development of the new satellite techniques to improve temperature and wind speed interpolations as well as investigation into the improvements of Dew point temperature at 2 m height (T_{dewp}). Incorporation of the MODIS land cover type data product will be included.

Year 3 will refine these new techniques, with an emphasis on outreach and development of web-based methods and visualization to provide the information to the public. outreach and development of web-based methods and visualization to provide the information to the public. By year 3, the bridging mission (NPOESS Preparatory Mission, NPP) for the next generation polar orbiting weather satellite program (National Polar Orbiting Environmental Satellite System, NPOESS) will be available (to be launched in late 2006 or early 2007).

This next generation data, particularly the optical, thermal and microwave imagers and the sounder data will be investigated for incorporation into the ETo model. This new system will operate into the late 2020's and this part of the study will prepare California to retain it's national cutting edge status for water management.

3 Monitoring and Assessment

There are several ways that our project can use MODIS data to aid validation of the input variables from interpolation and from GOES products and the projets ETo output product. These include direct comparison of temperature, vapor pressure, etc. but also empirical comparisons to land cover and process-based products, like estimates of net primary productivity (which should be correlated with ET).

Though the model above provides a single ET_0 value per pixel, the usefulness of this result is constrained by its quality. To support the use of model output it is necessary to provide, in conjunction with the resulting ET_0 values, information about the reliability of the predictions. For our model, interpolated data presents problems of undersampling and poorly distributed weather stations, while satellite imagery presents problems with the methods of retrieval and derivation used.

To determine the quality of the model we compare the results obtained in the model with those values measured by the cimis stations. Them we further verify the results by considering how the uncertainty in input data affects the results. To investigate the effects of input data uncertainty we performed both uncertainty and sensitivity analysis. This analysis are done spatially to identify those areas where the model provides high quality results and those that need further improvements. The uncertainty analysis studies the propagation of uncertainty from input data to model output. We use this information to establish the reliability of model results The sensitivity analysis identifies which input parameters are the most influential. We use this information to identify the improvements needed in the input data in order to most effectively reduce model output uncertainty.

By determining the combined influence of all the sources of uncertainty in model output it is possible to determine how realistic and reliable the results of the model are and how much confidence we can have on them. By determining which are the main contributors of uncertainty in the output, it is feasible to know where to improve the model to reduce output uncertainty most effectively.

4 Qualifications

Dr. Susan Ustin's Center for Spatial Technologies And Remote Sensing deals primarily with interpretation of remote sensing imagery, applications of geographic information systems, and landscape modeling of vegetation, hydrology, and climatology. CSTARS is proud to be a California Space Institute Center of Excellence. Our mission is to provide leadership and coordination of environmental remote sensing applications, education and outreach programs that promote core remote sensing and spatial technologies, and environmental content applications. The Center houses high-powered computers, software, and equipment to best utilize data from a variety of sensors - both multi-spectral and hyper-spectral.

The California Space Institute (CalSpace) is a multi-campus research unit (MRU) of the University of California, committed to excellence in research and education in aerospace-related sciences, engineering and technology. The Davis campus is home to the CalSpace Center for Agriculture, Natural Resources and Environment. The UC Davis CalSpace Center leads in remote sensing R&D with applications in agriculture and resource management. It is associated with the Center for Spatial Technologies and Remote Sensing and works closely with California growers and the agricultural industry. One of its major priorities is advancing precision agriculture and workforce training in remote sensing through public outreach.

Dr. Susan Ustin and Quinn Hart are technical leads on this proposal, and both have extensive experience with ET_0 through other contracts with the *CIMIS* program. Their CV's are included in an appendix to this proposal.

5 Outreach and Acceptance

CalSpace will host a web site for the daily ET_0 images, statisical results, and other data (mirrored to *CIMIS*), offering a query interface to daily datasets. Data will be provided daily to *CIMIS* (or at time intervals requested) for long term storage. CalSpace will produce a monthly archive of Statewide Daily ETo, and yearly archive of 10 day averages of ETo. Images of daily ETo will be produced for downloading by client users. A daily archive of intermediate data products and calibration programs and parameters will be available to *CIMIS*. All data, programs, and documentation produced by the project will use GPL licensed (open source).

The raw output of the receiving stations is about 2 GB/day and several data processing steps need to be done to evaluate data quality, calibrate sensor output, register the data to ground coordinates, and reduce the data volume to the specific data products needed for ETo estimation.

6 Benefits and Costs

A professional programmer and scientist will design the modifications to the ET_0 methodology. A graduate student and post-doctoral scholar will assist in the implementation and act as an interdisciplinary bridge between remote sensing scientists and *CIMIS* experts. Together, they will perform the analysis of satellite and *CIMIS* data to process it to physical variables and calculate ET_0. Costs are further summarized in the attached Benefits and Cost table (C1).

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Table C-1: Project Costs (Budget) in Dollars)

	Category (I)	Project Costs $ (II)	Contingency % (ex. 5 or 10) (III)	Project Cost + Contingency $ (IV)	Applicant Share $ (V)	State Share Grant $ (VI)	Life of investment (years) (VII	Capital Recovery Factor (VIII)	Annualized Costs $ (IX)
	Administration[1]								
	Salaries, wages	$210,979	0	$210,979	$0	$210,979	0	0.0000	$0
	Fringe benefits	$59,463	0	$59,463	$0	$59,463	0	0.0000	$0
	Supplies	$24,515	0	$24,515	$0	$24,515	0	0.0000	$0
	Equipment	$0	0	$0	$0	$0	0	0.0000	$0
	Consulting services	$0	0	$0	$0	$0	0	0.0000	$0
	Travel	$4,872	0	$4,872	$0	$4,872	0	0.0000	$0
	Other*	$25,984	0	$25,984	$0	$25,984	0	0.0000	$0
(a)	Total Administration Costs	$325,813		$325,813	$0	$325,813			$0
(b)	Planning/Design/Engineering	$0	0	$0	$0	$0	0	0.0000	$0
(c)	Equipment Purchases/Rentals/Rebates/Vouchers	$0	0	$0	$0	$0	10	0.0000	$0
(d)	Materials/Installation/Implementation	$0	0	$0	$0	$0	0	0.0000	$0
(e)	Implementation Verification	$0	0	$0	$0	$0	0	0.0000	$0
(f)	Project Legal/License Fees	$0	0	$0	$0	$0	0	0.0000	$0
(g)	Structures	$0	0	$0	$0	$0	0	0.0000	$0
(h)	Land Purchase/Easement	$0	0	$0	$0	$0	0	0.0000	$0
(i)	Environmental Compliance/Mitigation/Enhancement	$0	0	$0	$0	$0	0	0.0000	$0
(j)	Construction	$0	0	$0	$0	$0	0	0.0000	$0
(k)	Other (Specify)**	$74,957	0	$74,957	$0	$74,957	0	0.0000	$0
(l)	Monitoring and Assessment	$0	0	$0	$0	$0	0	0.0000	$0
(m)	Report Preparation	$0	5	$0	$0	$0	0	0.0000	$0
(n)	**TOTAL**	$400,770		$400,770	$0	$400,770			$0
(o)	Cost Share -Percentage				0	100			

1- excludes administration O&M.
*Administration Other includes Fee Remissions
**(k) Other includes 25% Indirect Costs on all expenses except Fee Remissions

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Table C-5 Project Annual Physical Benefits (Quantitative and Qualitative Description of Benefits)

Qualitative Description - Required of all applicants[1]				**Quantitative Benefits - where data are available** [2]
Description of physical benefits (in-stream flow and timing, water quantity and water quality) for:	Time pattern and Location of Benefit	Project Life: Duration of Benefits	State Why Project Bay Delta benefit is Direct[3] Indirect [4] or Both	Quantified Benefits (in-stream flow and timing, water quantity and water quality)
Bay-Delta Daily estimates of reference evapotranspiration improve general water use and planning. Archive of evapotranspiration improve long range planning	Daily for Bay-Delta	Continuous	Project is Indirect because the outcomes result in generally improved water use planning	Daily maps of spatial reference evapotranspiration. Improved spatial statistics of evaporanspiration.
Statewide Daily estimates of reference evapotranspiration improve general water use and planning. Archive of evapotranspiration improve long range planning	Daily for California	Continuous	**Not applicable.**	Daily maps of spatial reference evapotranspiration. Improved spatial statistics of evaporanspiration.

[1] The qualitative benefits should be provided in a narrative description. Use additional sheet.
[2] Direct benefits are project outcomes that contribute to a CALFED objective within the Bay-Delta system during the life of the project.
[3] Indirect benefits are project outcomes that help to reduce dependency on the Bay-Delta system. Indirect benefits may be realized over time.
[4] The project benefits that can be quantified (i.e. volume of water saved or mass of constituents reduced) should be provided.

CURRICULUM VITAE
Susan L. Ustin

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Director, DOE's Western Regional Center for Global Environmental Change
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Education

University of California, Davis, Ph.D. Botany, 1983; California State University, Hayward, M.A. Biology, 1978; California State University, Hayward, B.S. Biology, 1974

Professional Experience

1995-2001 Associate Director, DOE's Western Regional Center for Global Environmental Change (WESTGEC), University of California, Davis
1995-present, Director, U. C. Davis Space Grant Program
1999-present Professor of Environmental and Resource Science, Dept. of Land, Air, and Water Resources, University of California
1996-1999 Associate Professor of Resource Science, Dept. of L.A.W.R., U.C., Davis
1991-1996 Assistant Professor of Resource Science, Dept. of L.A.W.R., U.C., Davis
1990-1991 Assistant Research Resource Scientist, Dept. of L.A.W.R., U.C., Davis
1990-1992 Research Associate with NASA Ames Research Center, Moffett Field, CA

Honors

1992 - IEEE Geoscience and Remote Sensing Society Transactions Prize Paper Award.
2002 – Elected Fellow, The Remote Sensing and Photogrammetry Society
2004 – Outstanding Service, American Society of Photogrammetry and Remote Sensing
2004 – Elected Senior Member, Institute of Electrical and Electronic Engineers
2004 – SERDP Conservation Project of the Year

Panels and Professional Committees

NASA MODIS Science Team Member, 2004-present.
NPOESS Science Advisory Board, Northrop-Grumman, 2002-present.
U.C. Davis Representative to the University Corporation for Atmospheric Research, 1993-present
Resource21 Science Advisory Board for Landsat LDCM Mission, 2000-2002.
Advisory Board Member, Environmental (Remote Sensing) Baselining Initiative, Chevron, Corp. 1999-2002.
Executive Committee, U.C. California Space Institute 1993-2002
Member, National Research Council, Committee on Earth Studies, Space Studies Board, Commission on Physical Sciences, Mathematics and Applications. 1999. Review of NASA's Post-2002 Plan.
Executive Committee Member and Vice Chair, for the UC Digital Media Innovation Program (DiMI), 1998-2002
UC Davis Advisor for the NASA Ames Associates Internship Program, 1997-2000
Member, National Research Council, Committee on Earth Studies, Space Studies Board, Commission on Physical Sciences, Mathematics and Applications. 1997-2000. Review of the NPOESS Program.
Member, National Research Council, Ecosystems Panel, Board of Agriculture, Commission on Geosciences, Environment and Resources and the Commission on Life Sciences. 1997-1999. Review of the Ecosystems program in the U.S. Global Change Research Program.
Member, National Research Council, Board of Agriculture. 1995-1997. Assessing Crop Yield: Site-

specific farming, information systems, and research opportunities.
Science Team Member, Sierra Nevada Ecosystem Study (U.S. Congress Report), 1993-1996.
Science Team Member, NASA Earth Observing System (EOS), Interdisciplinary Science Team, Atmosphere-Biosphere Interactions, 1990-present
Chair, Graduate Ecosystem and Landscape Ecology Program in the Ecology Graduate Group, 1991-1997

Publications: 115 reviewed articles; >100 non-reviewed articles; >100 abstracts

Li, L. and S.L. Ustin, 2004. Application of AVIRIS data in detection of oil-induced vegetation stress at Jornada, New Mexico, Remote Sensing of Environment (accepted).

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Education

2002/08-PRESENT University of California, Davis. Enrolled in Ph.D program of the Graduate Group in Computer Science. Employee-Student status.

1990/06 University of Arizona. Master's of Science degree awarded in Optical Sciences. Thesis, *Surface and Aerosol Models for use in Radiative Transfer Codes.*

1987/05 University of Arizona. Bachelor of Science degree awarded May 1987 in Engineering Mathematics.

Professional Experience

1992/08–PRESENT University of California, Davis. Programmer/Analyst IV.

1990/09–1992/07 Scitec, Princeton, NJ. Scientist.

1988/08–1990/09 University of Arizona, Remote Sensing Group, Tucson. Graduate Student.

Synergistic Activities

Mr. Hart's research interests are in the field of Geographic Information Systems (GIS) and remote sensing. He is interested in distributed architectures, and spatial data discovery methods. Mr Hart is also interested in image processing, primarily for environmental modeling and decision making.

02–04 Mr. Hart was the technical lead, and program manager for a California Irrigation Management Information System, contract to provide spatial estimations of potential evapotranspiration for the State of California.

He is the technical architect of the California Spatial Information Library

He shares program management responsibilities for the University of California, Davis, CalSpace Center of Excellence.

Collaborators

Dr. Susan Ustin, University of California, Davis; Greg Greenwood, California Resources Agency; Kent Frame, Department of Water Resources;

Thesis Advisor

PH.D (currently enrolled) Dr. Michael Gertz, Assistant Professor, Department of Computer Science, University of California, Davis

M.S. Dr. Philip Slater, Professor Emeritus of Remote Sensing, Department of Optical Sciences, University of Arizona

Selected Publications

S.L. Ustin, Q.J. Hart, L. Duan, and G. Scheer. Vegetation mapping on hardwood rangelands in california. *International Journal of Remote Sensing*, 1996.

Q.J. Hart, S. L. Ustin, L. Duan, and G. Scheer. Estimating dry grass residues using landscape integration analysis. In Robert O. Green, editor, *Fourth Annual JPL Airborne Geoscience Workshop*, pages 89–92, Washington, D.C., Oct. 25-27 1993. NASA, Jet Propulsion Laboratory. JPL 93-26.

J.E. Pinzon, S. L. Ustin, Q. J. Hart, S. Jacquemoud, and M. O. Smith. Using foreground/background analysis to determine leaf and canopy chemistry. *Summaries of the Fifth Annual JPL Airborne Earth Science Workshop*, pages 129–132, January 1995.

S.L. Ustin, L-H. Szeto, Q.-F. Xiao, Q.J. Hart, and E.S. Kasischke. Vegetation mapping of forested ecosystems in central alaska. In *International Geoscience and Remote Sensing Symposium IGARSS '94*. California Institute of Technology, August 8-12 1994.

Davis, CA, January 10, 2005

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	Consulting services	$0	0	$0	$0	$0	0	0.0000	$0
	Travel	$4,872	0	$4,872	$0	$4,872	0	0.0000	$0
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(a)	Total Administration Costs	$325,813		$325,813	$0	$325,813			$0
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(f)	Project Legal/License Fees	$0	0	$0	$0	$0	0	0.0000	$0
(g)	Structures	$0	0	$0	$0	$0	0	0.0000	$0
(h)	Land Purchase/Easement	$0	0	$0	$0	$0	0	0.0000	$0
(i)	Environmental Compliance/Mitigation/Enhancement	$0	0	$0	$0	$0	0	0.0000	$0
(j)	Construction	$0	0	$0	$0	$0	0	0.0000	$0
(k)	Other (Specify)**	$74,957	0	$74,957	$0	$74,957	0	0.0000	$0
(l)	Monitoring and Assessment	$0	0	$0	$0	$0	0	0.0000	$0
(m)	Report Preparation	$0	5	$0	$0	$0	0	0.0000	$0
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**(k) Other includes 25% Indirect Costs on all expenses except Fee Remissions