ASSESSING AGRICULTURAL CONSUMPTIVE USE

INCLUDING REMOTE SENSING OF ACTUAL EVAPOTRANSPIRATION

IN THE UPPER COLORADO RIVER BASIN

PHASE 2 REPORT

May 2016

URS

CH2MHILL

Hydrologic Engineering, Inc.

TABLE OF CONTENTS

List of Tables

List of Figures

List of Appendices

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λE	latent heat
3-D	three-dimensional
AgriMet	agricultural weather network
ASCE	American Society of Civil Engineers
c	correction (*c*-factor)
CO_2	carbon dioxide
CoAgMet	Colorado Agricultural Meteorological Network
DOY	day of year
dT	near-surface temperature gradient
EC	eddy covariance
ET	evapotranspiration
ET_a	actual evapotranspiration
ETrF	reference ET fraction
ft^2	square feet
G	heat conducted to and from the soil
GIS	geographic information system
H	total sensible heat transported into the air
HEI	Hydrologic Engineering, Inc.
HPRCC	High Plains Regional Climate Center
HRSL	Hydrology and Remote Sensing Laboratory
Hz	Hertz
km	kilometer
LE	latent energy
LST	land surface temperature
NaN	not a number
NAPI	Navajo Agricultural Products Industry
NMCC	New Mexico Climate Center
m	meter
mm	millimeter
mm/d	millimeters per day
METRIC	Mapping EvapoTranspiration at High Resolution and Internalized Calibration

MOU	memorandum of understanding
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resource Conservation Service
O&M	operation and maintenance
PL	Public Law
Project	Assessing Agricultural Consumptive Use in the Upper Colorado River Basin Project
RAM	random access memory
Reclamation	United States Bureau of Reclamation
ReSET	Remote Sensing of Evapotranspiration
RH	relative humidity
RMSE	root mean square error
Rn	total available (net) radiation
QA	quality assurance
QC	quality control
SEBAL	Surface Energy Balance Algorithm for Land
SCAN	Soil Climate Analysis Network
SDM	Security Device Manager
SLC	Scan Line Corrector
SSEB	Simplified Surface Energy Balance
SSEBop	operational Simplified Surface Energy Balance method
Study Team	Assessing Agricultural Consumptive Use in the Upper Colorado River Basin Study Team
T_{air}	air temperature
T*cold*	temperature of the cold pixel
UCRB	Upper Colorado River Basin
UCRC	Upper Colorado River Commission
Upper Division	Colorado, New Mexico, Utah, and Wyoming
USGS	U.S. Geological Survey
WACNet	Wyoming Agricultural Climate Network

The four states of the Upper Division as defined in the Upper Colorado River Basin (UCRB) Compact (Colorado, New Mexico, Utah, and Wyoming), through the Upper Colorado River Commission (UCRC), requested that the United States Bureau of Reclamation (Reclamation) initiate a study to assess and improve consumptive use determinations. Reclamation then contracted with a consultant team led by URS, with assistance from CH2M Hill, Wilson Water Group, and Hydrologic Engineering, Inc. (HEI) to review and document the consumptive use methodologies used by the four Upper Division States and Reclamation, and to report on the state-of-the-art of remote sensing for consumptive use calculations and its potential applicability to the UCRB. The assessment is limited to the beneficial consumptive uses associated with direct irrigation and does not address other consumptive use and loss components in the UCRB.

The Assessing Agricultural Consumptive Use in the UCRB Study Team (Study Team) wishes to thank the technical staff of the four Upper Division States, the UCRC staff, and Reclamation staff – in particular staff at the Technical Services Center in Denver – for their technical assistance on the Assessing Agricultural Consumptive Use in the UCRB Project (Project).

The intent of Phase I of the study, completed in November 2013, was to:

1. Identify the differences in consumptive use methodologies used by the four Upper Division States and Reclamation;
2. Provide the basis for a discussion among these entities as to whether changes to the methodology used by Reclamation are appropriate at this time; or
3. Provide a recommendation as to whether the current state-of-the-art of remote sensing is sufficiently advanced for the Upper Division States and Reclamation to further investigate its implementation within the UCRB.

In Phase II, the Study Team was directed to make recommendations for the appropriate number and locations of Extended Climate Stations and eddy covariance (EC) Towers, and perform an analysis based on the amount of irrigated acreage covered by the number of existing Extended Climate Stations to recommend the number and locations of new stations to install. Additionally, the Study Team was directed to install and operate, an EC tower for six months, and to use the resulting data to provide “ground truth” for the evaluation of various remote sensing models for the estimation of actual consumptive uses.

EXTENDED CLIMATE STATIONS

Section 2 of this report includes information on the procedures used to assess existing Extended Climate Stations and identify locations to install new ones, as well as information on the funding requirements involved with these stations. Section 2 also provides information on the final site selection process for Extended Climate Stations.

Section 2.1 discusses the identification of existing Extended Climate Stations in the Upper Division States during Phase I of the Project, and the procedures used to determine their suitability for estimating crop consumptive use. Section 2.1 also provides a list of proposed Extended Climate Stations and estimated irrigated acreages that would be covered by those stations.

Section 2.2 provides estimates of installation and operation and maintenance (O&M) costs, as well as information on procedures for maintenance, calibration, and data review.

Section 2.3 discusses coordination with state Climatologists and/or state climate network representatives to identify land owners interested in allowing Extended Climate Stations on their land, and includes information on requirements regarding land access and training on equipment maintenance.

EDDY COVARIANCE TOWERS

Section 3 provides a discussion of the EC process, including an introduction to evapotranspiration (ET) measurement techniques, advantages of the EC technique, assumptions of EC, and recommended readings for EC. Information on physical infrastructure requirements, footprints, data stewardship techniques, and location considerations for EC towers is also included.

Section 3.1 includes background information on EC and ET, including a discussion of ET measurement techniques based on three methods: energy balance, mass balance, and physical transport.

Section 3.2 includes a discussion on the advantages and synergies of EC, including taking representative measurements of a large land area, and providing independent measurements that are based on turbulent transport. EC is currently seen as the standard for measuring ET in the field, and is essential to flux estimates for multiple networks.

Section 3.3 discusses assumptions of the EC method with regards to turbulence, land surface, mean vertical wind, and stationarity. The EC measurement technique can be disrupted if either of the first two assumptions are violated.

Section 3.4 provides information on recommended readings on EC, and Section 3.5 provides a description of the infrastructure required for EC techniques. This section includes a discussion of sensor types and the packages available, and goes on to discuss the following information:

- The sensor selection process.
- Additional optional sensors that are available.
- Physical infrastructure that is necessary to support EC data collection, including suspending EC instruments above the land surface, providing electricity to equipment, protecting instruments from local wildlife, and grounding electrical structures.
- The importance of real-time telemetry of raw data and configurations to support it.
- The site survey that should be performed at the time of setup.
- EC tower maintenance, including recalibration of sensors, checking of electronics, and other necessary practices for upkeep.
- Selection of EC tower locations within the field sites based on meteorological data.
- Safety hazards that should be addressed before initiating field work.
- Lessons learned and potential failure modes of EC.

Section 3.6 discusses specialized data handling and analysis techniques used for EC; the raw data must be processed in several steps before the ET can be determined, including:

- Initial screening, which includes removing suspect data flagged by the system, determining tower shadow (regions of disturbance), and checking for improbable values based on physical constraints.
- De-Spiking, or removing data "spikes" that fall outside certain standard deviations.
- Density corrections.
- Planar fit.
- Ogive analysis.
- Breaking data into averaging intervals.
- Blocking de-trending.
- Optional spectral analysis.
- Flux calculation.
- Additional flux corrections.

Section 3.7 discusses footprints, or the region of influence of the flux measured by EC techniques, and provides information on the variables and assumptions that go into flux calculations.

Section 3.8 provides a description of the skills personnel should assess for O&M and data stewardship of the EC method.

Section 3.9 includes information on the 2015 growing season, including information on data sampling as well as results for daily and cumulative ET.

Section 3.10 contains a map of the study region with existing and planned EC towers, as well as specific considerations used to identify locations for installation of EC towers. These criteria were used to develop a list of first- and second-choice candidate locations for additional EC towers. Precise locations will be finalized after a field assessment by an EC expert and will depend on available funds and preferred outcomes. Section 3.10 concludes with a discussion of the advantages and disadvantages of mobilizing EC towers.

REMOTE SENSING MODELING ASSESSMENTS

Section 4 of this report evaluates the practicality of applying remote sensing data to calculate actual consumptive use of irrigated areas in the UCRB. It includes information to assist the Upper Division States and Reclamation in assessing whether to:

1. Continue investigating the current state of technology associated with remote sensing;
2. Move towards a preferred remote sensing method with a small-scale pilot study to potentially investigate the ease of use and accuracy of different methods; or
3. Adopt a remote sensing method that is best suited to the UCRB.

Background and Methods

The objectives of the remote sensing aspects of this Project were focused on evaluation of the operational applications of various remote sensing methods to estimation of crop ET over agricultural fields of the UCRB. The methods analyzed included the Reconstructed Mapping EvapoTranspiration at High Resolution and Internalized Calibration (R-METRIC) method and the operational Simplified Surface Energy Balance (SSEBop) method in Colorado, New Mexico, Utah, and Wyoming. Additional space-based SSEBop estimates of ET were made in Colorado. These alternative approaches investigated the influence of: 1) the number of scenes analyzed, 2) cold pixel selection, and 3) automatic hot and cold pixel selection. Satellite methods were compared to estimates of reference evaporation in each state, respectively. A detailed comparison between the satellite methods and a direct measurement of actual ET, measured with an EC tower, were performed in Colorado. The comparison (Figure ES-1) between the EC tower and the satellite estimation methods was made for the subset of satellite image 'pixels' that corresponded directly to the measurement footprint of the EC tower. Inter-comparisons were performed only when data from all sources were available.

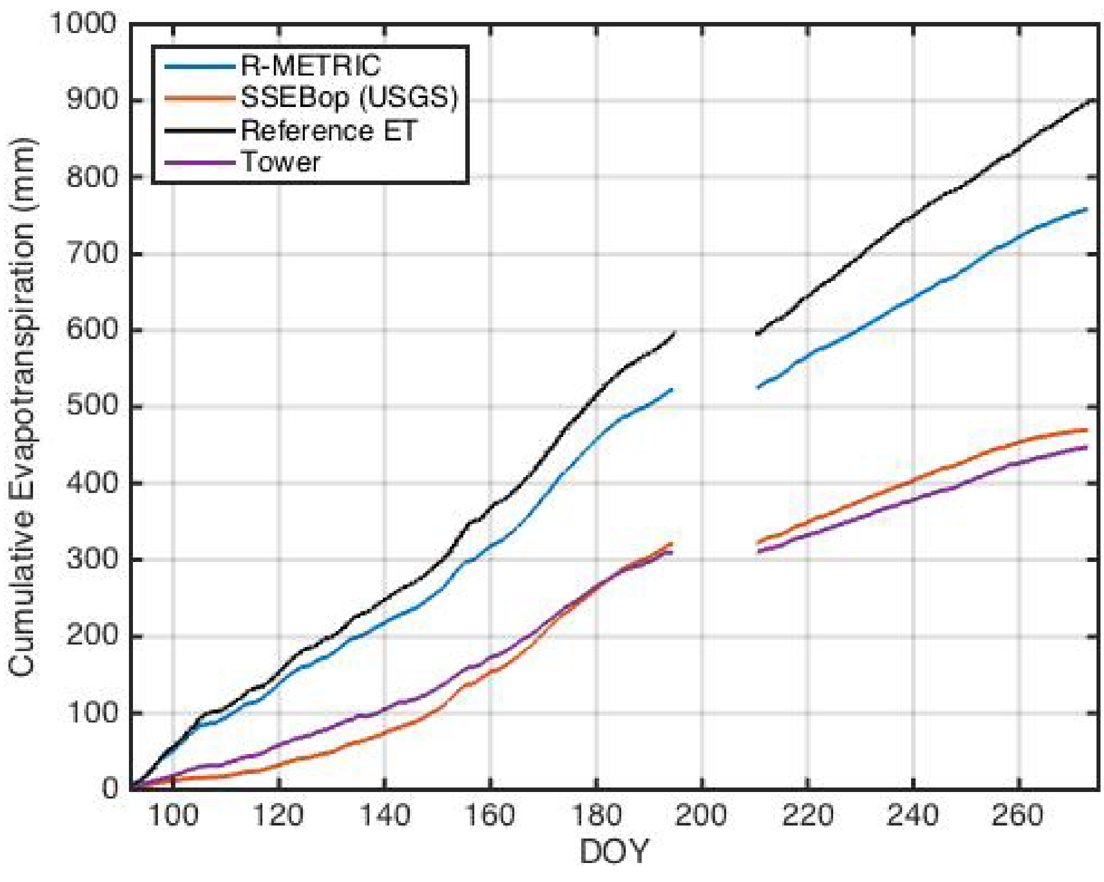

Figure ES-1 Comparison of EC tower cumulative ET ground-truth data for the growing season compared to various remote sensing estimating methods; Penman-Monteith reference ET is also plotted as an upper boundary, indicating the EC tower site near Rifle, Colorado was under some water stress during the 2015 growing season

Lessons Learned

1. All remote sensing methods over-estimated cumulative seasonal ET relative to the EC tower measurements.
2. The Penman-Monteith reference ET results were higher than any of the remote sensing estimating methods and the EC tower data indicating that the site of the EC tower has some water stress, and that all of the methods constrained the ET estimate to some degree while showing similar patterns through the season of high, moderate, and low ET days.
3. SSEBop using the U.S. Geological Survey (USGS), which determines cold reference values for each pixel using air temperature and an automated correction coefficient called *c*-factor, was the most similar to the EC tower measurements, for this particular comparison.
4. R-METRIC using hot and cold pixel selection by closely following the METRIC Manual Guidelines, had a substantial bias and reported the highest ET of all remote sensing methods.

Remote sensing methods have promise and their potential for automation could lead to an economical approach to estimate agricultural consumptive water use throughout the entire UCRB. Space-based ET estimates are high relative to the EC tower, but the SSEBop algorithm showed the highest level of fidelity, for this comparison.

Recommendations

If the potential of space-based ET estimation is to be realized, continued confidence building in the methods of data analysis and interpretation is necessary. There is value in having a set of ‘ground-truth’ sites to determine the level of ET accuracy. Moving forward, a modest EC tower network is recommended that would include a minimum of one EC tower in each state of the UCRB. The purpose of this expansion is to test and build confidence in remote sensing ET estimation methods. This includes evaluating the performance of remote sensing methods covered in this report and possibly newer methods over a wider range of climatological regimes. The influence of hot and cold pixel selection methodologies, in particular automated pixel selection methods for R-METRIC, should be investigated in more detail. This portion of the ET estimation algorithms was a source of significant positive bias in this study. An automated boundary pixel selection procedure would also lead to labor savings. The Upper Colorado River Commission (UCRC) should be open to new and evolving methods of ET determination using remote sensing platforms. Although Landsat 8 will remain the preferred platform for the foreseeable future, new platforms are in the planning stages and new algorithms for data analysis are evolving.

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2. Provide the basis for a discussion among these entities as to whether changes to the current methodology used by Reclamation are appropriate at this time; or
3. Provide a recommendation as to whether the current state-of-the-art of remote sensing is sufficiently advanced for the Upper Division States and Reclamation to further investigate its implementation within the UCRB.

In Phase II, the Study Team was directed to:

1. Estimate the appropriate number and locations of Extended Climate Stations desired based on the location of irrigated acreage and the distance between Extended Climate Stations.
2. Identify the existing Extended Climate Stations that meet the defined criteria and that can be used to calculate potential ET.
3. Recommend existing temperature/precipitation stations that can be upgraded to measure extended climate data, specifically solar radiation and wind speed.
4. Estimate the required number of new Extended Climate Stations and recommend locations for those.
5. Recommend new Extended Climate Stations based on weighing cost versus benefits.
6. Recommend, develop, and document procedures for assigning current and future climate stations to irrigated land locations.
7. Document standard American Society of Civil Engineers (ASCE) procedures for reviewing, correcting, and filling/supplementing extended raw climate data.
8. Estimate the required number of EC towers and recommend locations for those. Note: The number of EC towers was actually determined by budgetary constraints. The purpose of the EC towers is to serve as ground-truth for the remote sensing data analysis described in Section 4.
9. Work with Reclamation and the States to recommend individual EC tower ownership (e.g., part of current state network, agricultural weather network [AgriMet], etc.). Similar to the Extended Climate Station recommendation approach above, an “appropriate” number and associated locations will be examined and then weighed against costs and benefits to provide the final recommendation.

10. Assess the potential for allowing EC towers to be moved over a determined period of time to cover more irrigated acreage. The advantage of having a mobile EC tower, defined as a tower that may be moved from one growing season to another but not within a growing season, is that EC tower data for other vegetation canopies can be collected, processed, and used as ground-truth for the remote sensing data analysis. The disadvantage is the cost of moving the EC tower and the multiple installation costs.
11. Estimate installation and O&M costs including procedures, schedules, and responsible entities. Costs will be, in part, based on information gathered through interviews with state and Federal network operators.
12. Provide cost breakdowns for equipment and installation of EC towers.
13. Develop O&M costs that include routine maintenance costs, costs to calibrate sensors, and costs to stock backup sensors to allow for timely replacement of any failing sensors when taken off-line for repairs and maintenance.
14. If mobile EC towers are recommended, examine the frequency and costs associated with relocation.
15. Recommend data retrieval, processing, quality assurance (QA), quality control (QC), distribution, and storage procedures, and develop associated cost estimates.
16. Review existing network procedures and identify if existing networks follow or deviate from the recommendations.
17. Make recommendations for greater consistency across state and Federal networks, if necessary.

Appendix A contains meeting minutes and conference call notes that reflect the efforts of the Study Team in progressing this Project between Phase I and Phase II. Appendix B contains the final memorandum of understanding (MOU) concerning the UCRB and the installation and maintenance of consumptive use instrumentation.

Water allocation among the states in the UCRB is stipulated by the Colorado River Compact of 1922, and the Upper Colorado River Compact of 1948. These are the principal (but not the sole) documents of the “Law of the River.” This Phase II Report focuses on estimation of consumptive use by irrigated agriculture in the four Upper Division States. Article VI of the Upper Colorado River Compact directs that the UCRC shall *determine the quantity of consumptive use* of water; Article VIII directs that the UCRC shall have the power to, among other things, make findings as to the quantity of water used each year in the states in the UCRB, make findings as to the quantity of water deliveries at Lee Ferry during each water year, and make findings as to the necessity for and the extent of curtailment of use. Additionally, the UCRC is directed to make and transmit an annual report covering its activities to the Governors of the four Upper Division States and the President of the United States.

Reclamation is directed by Title VI of the 1968 Colorado River Basin Project Act (Public Law [PL] 90-537) to *make reports of the annual consumptive uses and losses*, on a five-year basis, beginning with the period starting on October 1, 1970. Reclamation is further directed to prepare these reports in consultation with the states and the UCRC, and to report to the President of the United States, the Congress, and to the governors of the states signatory to the Colorado River Compact. Reclamation is also to condition any contracts for delivery of water originating from the UCRB upon the availability of water under the Colorado River Compact. Since 1971, Reclamation has both estimated and reported UCRB consumptive use in its Consumptive Uses and Losses Report.

Efficient administration of the Colorado River Compact requires accurate estimates of agricultural consumptive use within the UCRB. More than 80 percent of the total consumptive use of water within the UCRB is from irrigated agriculture.

As the demands on the water resources of the Colorado River intensify, it is becoming even more important to document both the potential consumptive use (i.e., the amount of water crops would use if given a full supply), as well as the actual consumptive use (i.e., the amount of water crops actually consume). Many areas in the UCRB consistently exist on a “short supply,” depending upon direct flow or limited reservoir storage to supply the crops. The accurate and defensible calculation and reporting of the shortages that the UCRB incurs during its normal operations is necessary for any future negotiations on shortage allocations.

Monitoring Network Recommendation: Sections 2 and 3 of this report documents the recommendations for the network of Extended Climate Stations and EC towers that would support a move towards an improved method of documenting the agricultural consumptive uses in the UCRB.

Remote Sensing Assessment: Section 4 of this report describes the potential application of remotely sensed data to the calculation of actual ET of irrigated lands in the Colorado River Basin of the Upper Division States.

Recommendations: This Phase II Report provides the basis for the following recommendations jointly proposed by the Upper Division States, Reclamation, and the UCRC.

- Develop detailed documentation of the procedures Upper Division States use to develop their irrigated acreage assessment to provide a clear understanding of the quality of irrigated acreage data to serve as the basis for the UCRB potential consumptive use estimates.
- Install and maintain additional Extended Climate Stations that measure the daily parameters required for the Penman-Monteith potential consumptive use method throughout the UCRB to ensure adequate spatial coverage.
- Develop protocols for daily climate data QC, data dissemination, and archiving based on the experience gained from current Extended Climate Station networks to apply to both existing and recommended additional data collection efforts.
- Continue to investigate the procedures required to move to the Penman-Monteith methodology to estimate potential consumptive use throughout the UCRB.
- Investigate the applicability of using a monthly versus daily effective precipitation analysis with a daily potential consumptive use method.

- Investigate alternate methods for estimated actual consumptive use where diversion records and estimates of farm deliveries do not exist, specifically the remote sensing data methods discussed in Section 4.
- Develop a protocol to ensure the method used to determine potential consumptive use, actual consumptive use, and agricultural water shortages is consistent and/or comparable for the entire UCRB, including development of clear and defensible fully documented procedures for QA/QC and review by the Upper Division States.
- Continue additional investigations to determine the cost and effort necessary to implement a physically based method incorporating components of the radiation and energy balance for the entire UCRB, as remote sensing techniques have not been routinely applied to areas of this size.
- Install and maintain up to four EC towers at strategic locations in the UCRB to provide the evaporation flux data necessary for operations.

This section includes recommendations for the appropriate number and locations of Extended Climate Stations and EC towers, and includes cost-benefit analyses based on the amount of irrigated acreage covered by the existing number of stations. Costs to install, operate, and maintain the measurement equipment, plus costs to manage and store the raw data measured, have been estimated. Issues associated with land ownership, access, leasing, and permitting are discussed, along with procedures for reviewing, correcting, and filling/supplementing data for use in estimating potential ET.

The following general procedure was followed to recommend the use of existing Extended Climate Stations and to propose new Extended Climate Station locations for use in estimating crop consumptive use to support the Consumptive Uses and Losses Reporting. This procedure was recommended to and approved by the Study Team:

1. Assess the suitability of existing Extended Climate Stations in each of the Upper Division States.
2. Identify additional Extended Climate Stations planned in each state.
3. Identify the acreage that could reasonably be covered by existing and planned Extended Climate Stations by reviewing topography and temperature variation as determined from other climate stations (e.g., National Oceanic and Atmospheric Administration [NOAA]). Identify the remaining acreage that is not covered by existing or planned Extended Climate Stations.
4. Focusing on areas with significant irrigated acreage not covered by existing sites, identify the "wish list" of locations for new sites.
5. Prioritize new site locations based on acreage that could be reasonably covered by a new Extended Climate Station.
6. Coincide EC towers with existing or proposed Extended Climate Station locations. Alternatively, the EC towers could contain appropriate instrumentation to collect that data.

2.1 APPROACH AND RESULTS – STATION SITING

Existing Extended Climate Stations (i.e., stations that measure parameters required for ASCE Standardized Penman-Monteith calculations to estimate potential ET) locations were identified in the Upper Division States during Phase I of the Project. The Phase I effort did not include reviewing each Extended Climate Station to identify its suitability for long-term use in estimating crop use. In Phase II, the climate network administrators in the Upper Division States were contacted to determine the following:

- Are the Extended Climate Stations located in agricultural settings?
- Are there routine instrumentation maintenance and calibration procedures in place that meet the ASCE standards?
- Do the network administrators perform appropriate QA and QC measures of the collected data using standard ASCE procedures?

There were several sites identified in Colorado and Utah that were not located in an agricultural setting or that did not meet the site-distance criteria for location. For example, one site in Colorado was located under an orchard canopy; while another site was located in the parking lot of an agricultural research center. In Utah, several sites were located in high desert areas and intended for purposes other than estimating agricultural use.

A network of stations in Utah managed by the Emery County Conservancy District was identified as under-funded and potentially not properly maintained. In addition, the Natural Resource Conservation Service (NRCS) Soil Climate Analysis Network (SCAN) stations are generally located at airports to help with real-time weather information. The Utah State Climatologist added new AgriMet stations that generally cover the same region; therefore, the Emery County and NRCS SCAN stations are not necessary for the Project. In New Mexico and Colorado, measured data is currently published as-is, and it is the user’s responsibility to perform QC and correction procedures prior to using the data for analyses. Wyoming currently relies on the High Plains Regional Climate Center (HPRCC) Automated Weather Data Network to perform data QC and corrections, manage the raw and corrected data, and make the data available to the public.

Since the publication of the Phase I Report (November 2013), the Utah State Climatologist has worked closely with AgriMet staff to install new Extended Climate Stations in the UCRB in Utah. Each of the new sites is located in an agricultural setting. In addition, Utah worked with AgriMet to identify two additional locations: one on agricultural land served from the Paria River; and one on agricultural land in Castle Valley near Moab.

The Colorado Agricultural Meteorological Network (CoAgMet) installed five new stations in Colorado in 2015. One additional Extended Climate Station has been funded and is planned for installation in 2016 in the upper Uncompahgre Basin near Ridgway.

Two Extended Climate Stations are located on lands irrigated by the Navajo Indian Irrigation Project. These stations were installed by the New Mexico Climate Center (NMCC); however, funding has restricted its ability to assist with Extended Climate Station maintenance. The stations are currently operated by the Navajo Agricultural Products Industry (NAPI).

The Wyoming State Engineer’s Office has purchased equipment and plans to install five new Extended Climate Stations in 2016. Each of the new Extended Climate Stations will be located in agricultural settings and managed as part of the Wyoming Agricultural Climate Network (WACNet).

The amount of irrigated acreage for which climate could be represented by existing and already planned for installation Extended Climate Stations was estimated based on reviewing topography, published average monthly temperature isohyetal maps, and temperature variation as determined from other climate stations (e.g., NOAA). The Kriging and Theissen Polygon approaches were considered to assign Extended Climate Stations to specific acreage, but were not recommended by the Study Team due to the non-contiguous nature of the irrigated acreage in the UCRB. A more subjective approach was used to site new stations in agricultural areas with more than 7,000 irrigated acres.

Table 2-1 shows the list of existing (i.e., already installed) and planned (i.e., planned for installation by AgriMet or state agencies independent of this Project) Extended Climate Stations and the estimated acreage that can be reasonably represented by each. Around 66 percent of the irrigated acreage in the UCRB can be reasonably represented by existing or planned Extended Climate Stations. Figures 2-1 through 2-4 show the location of existing and planned Extended Climate Stations and the general outline of acreage that could be represented by each (in black).

Note that where several existing Extended Climate Stations can cover irrigated acreage, there is an opportunity to use a weighted combination of Extended Climate Stations. As climate data is collected, the data can be reviewed to determine where acreage may be better represented by more than one Extended Climate Station. The data can also be used to enhance existing bias-corrected gridded climate and reference ET data sets.

Table 2-2 lists proposed stations and the estimated acreage they can represent. The general locations of the proposed Extended Climate Stations and the general outline that could be represented by each (in red) are also shown on Figures 2-1 through 2-4. The proposed Extended Climate Stations can reasonably represent an additional 22 percent of the acreage in the UCRB. About 88 percent of total acreage in the UCRB can be represented by existing, planned, and proposed Extended Climate Stations.

As shown on Figures 2-1 through 2-4, there are some irrigated areas that may not be accurately covered by an existing, planned, or proposed Extended Climate Station. These areas are generally smaller agricultural areas and do not warrant the cost of an additional Extended Climate Station. In the UCRB, about 12 percent of the irrigated acreage fits into this category. These smaller areas of irrigated acreage that are not within the outline of an Extended Climate Station can be represented by using weighted climate data at two or more nearby stations or by using bias-corrected gridded climate and reference ET data sets. The determination of climate assignments to irrigated acreage not shown as covered by existing or prosed Extended Climate Stations should be finalized as climate data is collected and the variance in climate parameters is known.

The new Extended Climate Station located near Silt, Colorado was coupled with an EC tower during the 2015 irrigation season. It is important that the locations selected for additional EC towers coincide with existing or proposed Extended Climate Stations or contain the appropriate instrumentation to collect that data. Although siting criteria for EC towers is more restrictive than siting criteria for Extended Climate Stations, many of the existing and proposed sites are ideal locations to include EC towers.

Table 2-1 Existing and planned extended climate stations

Extended Climate Station Name	Climate Network	State	Status	Irrigated Acreage
Bridger Valley	WACNet	WY	Existing	74,000
Boulder	WACNet	WY	Existing	53,000
Budd Ranch	WACNet	WY	Existing	43,000
Upper Green	WACNet	WY	Existing	39,000
Farson	WACNet	WY	Existing	21,000
Upper Green near Daniel	WACNet	WY	Planned	39,000
Henry’s Fork	WACNet	WY	Planned	23,000
Little Snake Valley near Baggs	WACNet	WY	Planned	23,000
Green River near La Barge	WACNet	WY	Planned	13,000
Hams Fork near Granger	WACNet	WY	Planned	10,500
Pleasant Valley	AgriMet	UT	Existing	38,500
Duchesne	AgriMet	UT	Existing	29,500

Table 2-1 Existing and planned extended climate stations

Extended Climate Station Name	Climate Network	State	Status	Irrigated Acreage
Pelican Lake	AgriMet	UT	Existing	31,000
Elmo	AgriMet	UT	Existing	26,500
Huntington	AgriMet	UT	Existing	20,000
Ferron	AgriMet	UT	Existing	13,000
Castle Dale	AgriMet	UT	Existing	10,500
Tropic (Paria River)	AgriMet	UT	Planned	3,500
Castle Valley near Moab	AgriMet	UT	Planned	3,000
Delta	CoAgMet	CO	Existing	90,000[1]
Montrose	CoAgMet	CO	Existing	
Olathe	CoAgMet	CO	Existing	
Olathe 2	CoAgMet	CO	Existing	
Eckert	CoAgMet	CO	Existing	58,500
Gunnison	CoAgMet	CO	Existing	53,500
Yellow Jacket	CoAgMet	CO	Existing	50,500
Silt	CoAgMet	CO	Existing	45,000
CSU Fruita Expt Station	CoAgMet	CO	Existing	39,000
Carbondale	CoAgMet	CO	Existing	25,500
Hayden	CoAgMet	CO	Existing	17,500
Orchard Mesa	CoAgMet	CO	Existing	10,500
Mancos	CoAgMet	CO	Existing	10,000
Cortez	CoAgMet	CO	Existing	9,000
Towaoc	CoAgMet	CO	Existing	7,000
Upper Uncompahgre	CoAgMet	CO	Planned	10,000
Navajo Block 1	NAPI	NM	Existing	38,000
Navajo Block 9	NAPI	NM	Existing	24,500
Farmington	NMCC	NM	Existing	14,500
Total Acreage Covered by Existing or Planned Extended Stations	**1,017,000**			

Notes:
[1]Extended Climate Stations all cover acreage under the Uncompahgre Project.
AgriMet = agricultural weather network
CoAgMet = Colorado Agricultural Meteorological Network
NAPI = Navajo Agricultural Products Industry
NMCC = New Mexico Climate Center
WACNet = Wyoming Agricultural Climate Network

Table 2-2 Proposed extended climate stations

Proposed Extended Climate Station Name	Climate Network	State	Irrigated Acreage
Neola Area	AgriMet	UT	35,000
Vernal	AgriMet	UT	34,500
Loa/Bicknell Area	AgriMet	UT	16,500
Los Pinos River	AgriMet/CoAgMet	CO	39,500
Kremmling	AgriMet/CoAgMet	CO	33,500
Steamboat Springs	AgriMet/CoAgMet	CO	33,500
Collbran	AgriMet/CoAgMet	CO	24,500
San Miguel	AgriMet/CoAgMet	CO	24,500
Marvine Ranch	AgriMet/CoAgMet	CO	22,500
Animas/Florida River	AgriMet/CoAgMet	CO	19,000
Fraser/Upper Colorado	AgriMet/CoAgMet	CO	15,000
La Plata River	AgriMet/CoAgMet	CO	12,500
Pagosa Springs	AgriMet/CoAgMet	CO	9,500
Aztec	AgriMet/NMCC	NM	15,000
Total Acreage Covered by Proposed Extended Stations	**335,000**		

Notes:
AgriMet = agricultural weather network
CoAgMet = Colorado Agricultural Meteorological Network
NMCC = New Mexico Climate Center

2.2 FUNDING REQUIREMENTS

The existing Extended Climate Stations shown in Table 2-1 have be installed and historically maintained through individual state funding. It is critical that the states recognize the importance of those stations to the UCRB Consumptive Uses and Losses Reporting and work towards assuring long-term funding for maintenance, calibration, and data QA/QC. Table 2-3 shows the estimated annual funding requirements, by state, to assure these stations can be used as part of an UCRB climate network.

Table 2-3 Annual funding requirements for existing and planned extended climate stations

Cost Item	Wyoming	Utah	Colorado	New Mexico
Number of Existing or Planned Extended Climate Stations	10	9	16	3
Annual Operation and Maintenance ($1,750 per year per station)	$17,500	$15,750	$28,000	$5,250
Data QA/QC ($500 per year per station)	$5,000	$4,500	$8,000	$1,500
Annual Cost	**$22,500**	**$20,250**	**$36,000**	**$6,750**

Note:
QA/QC = quality assurance/quality control

The individual states and Reclamation have approved and secured Upper Division states MOU funds to cover estimated installation and the first year's annual O&M and data QA/QC costs for the 14 proposed Extended Climate Station as shown in Table 2-4. The following is a detailed explanation of the costs included in Table 2-4.

- To help assure the Extended Climate Stations are maintained and calibrated to current ASCE standards, staff with Reclamation's AgriMet climate network will work with Colorado and New Mexico to develop calibration kits and review maintenance and calibration procedures for Colorado, New Mexico, and Wyoming. The cost for the kits and training, including travel costs, was estimated by AgriMet staff to be $3,000 per state. Note that AgriMet has already developed a calibration kit and provided training to Utah. Wyoming also has a calibration kit and procedures in place so the costs in Table 2-4 are for Colorado and New Mexico only.
- To help assure that the QC and any required filling of climate data is performed to current ASCE standards, AgriMet staff will work with Colorado and New Mexico to develop data review procedures. The $5,000 cost per state for AgriMet staff to assist in developing consistent QC procedures includes travel time to each state. Wyoming and Utah have QC procedures in place that meet ASCE standards.
- O&M of new Extended Climate Stations will be each state's responsibility and is estimated at $1,750 per station per year. O&M costs include data communication costs; site visits; and sensor cleaning and calibration. Note that New Mexico does not currently have funding to maintain and calibrate its three existing stations; therefore, those stations are included with the cost for the proposed Extended Climate Stations.
- Annual data QA/QC costs include meteorological data and metadata management, and data QC for new Extended Climate Stations plus the three existing Extended Climate Stations in New Mexico.
- Reclamation will cover 1/5 of the costs associated with the new Extended Climate Stations separate from the Upper Division States MOU funds.

Table 2-4 Costs for proposed extended climate stations

Cost Item	Unit Costs	Number Required	One-Time Costs	Annual Costs	Proposed Reclamation Share
Purchase and Install New Extended Climate Station	$9,000	14	$126,000	N/A	N/A
Develop Calibration Kits and Review/Assist with Calibration Processes	$3,000	2	$6,000	N/A	N/A
Assist with Development and Review of Data QA/QC Process	$5,000	2	$10,000	N/A	N/A
Operation and Maintenance	$1,750	15	N/A	$26,250	N/A
Data QA/QC	$500	15	N/A	$7,500	N/A
First Year Costs	**$175,750**				**$35,150**
Subsequent Year Annual Cost	**$33,750**				**$6,750**

Note:
N/A = not applicable

Since Reclamation funding will be used to purchase the Extended Climate Stations (or EC towers), they will maintain ownership of the stations. However, Reclamation can contract with the climate station network administrators to perform O&M on the equipment.

2.3 FINAL SITE SELECTION

State Climatologists and/or state climate network representatives routinely work with land owners and local conservation districts in their states to site climate stations and have agreed to assist the Study Team in completing the following steps:

1. Identify land owners that may be interested in allowing an Extended Climate Station to be located on their land.
2. Finalize the land access agreements and work with land owners to select the final site that meets the ASCE criteria.
3. Schedule installation and set expectations with the land owners regarding required access for scheduled equipment maintenance.
4. Train the land owners on simple maintenance issues that may be required periodically (e.g., cleaning dirt off a sensor or adjusting a stuck wind gage).

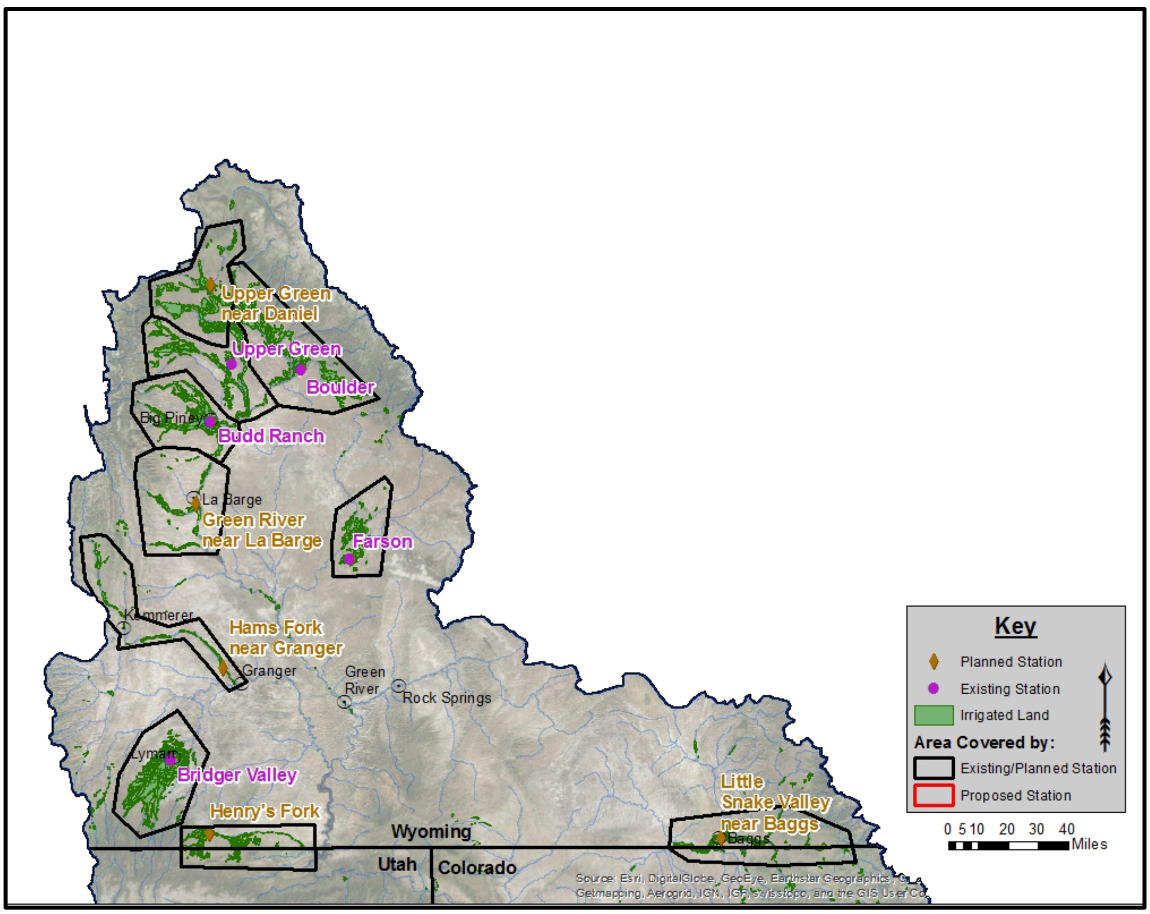


Figure 2-1 Wyoming extended climate stations and estimated coverage

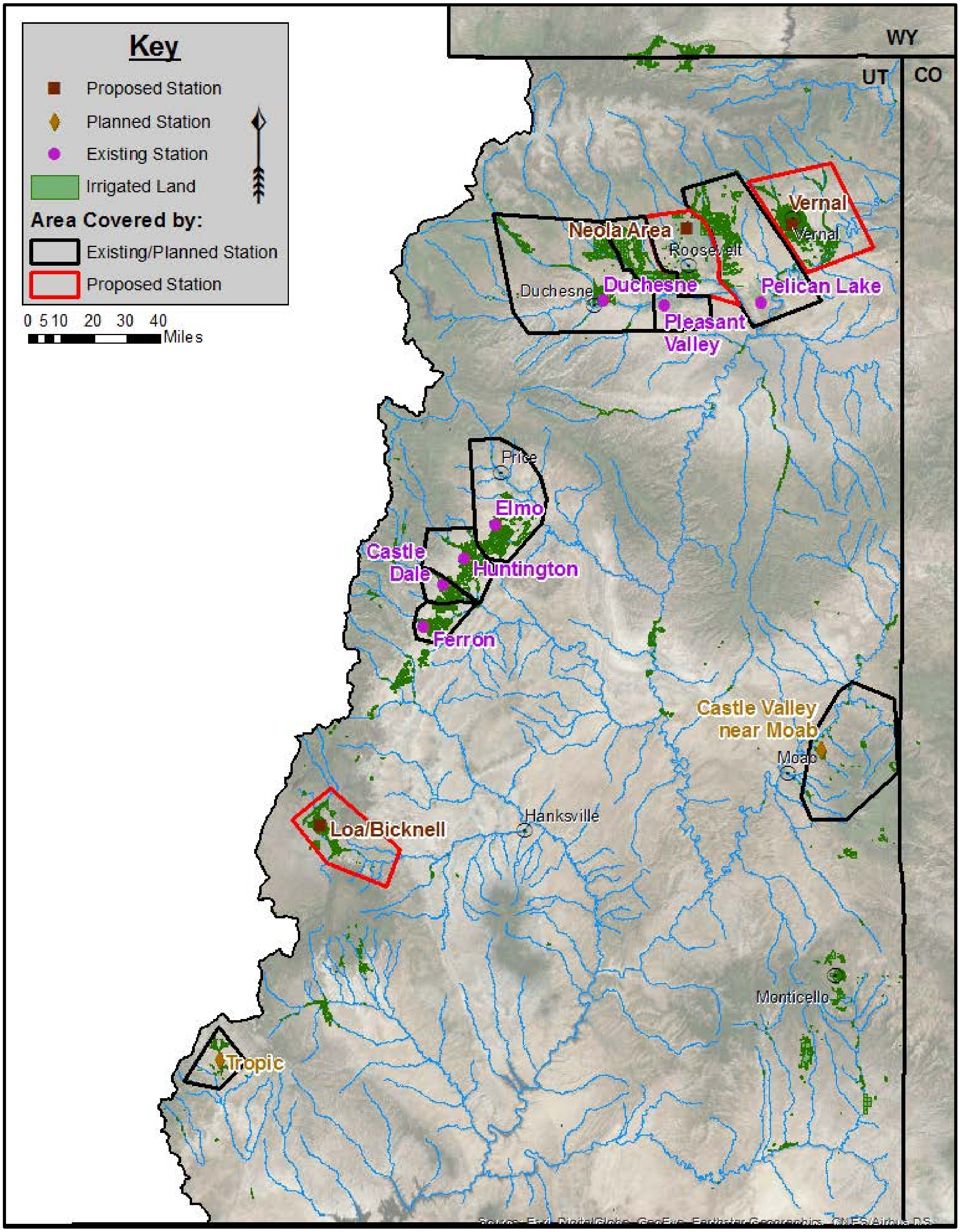


Figure 2-2 Utah extended climate stations and estimated coverage

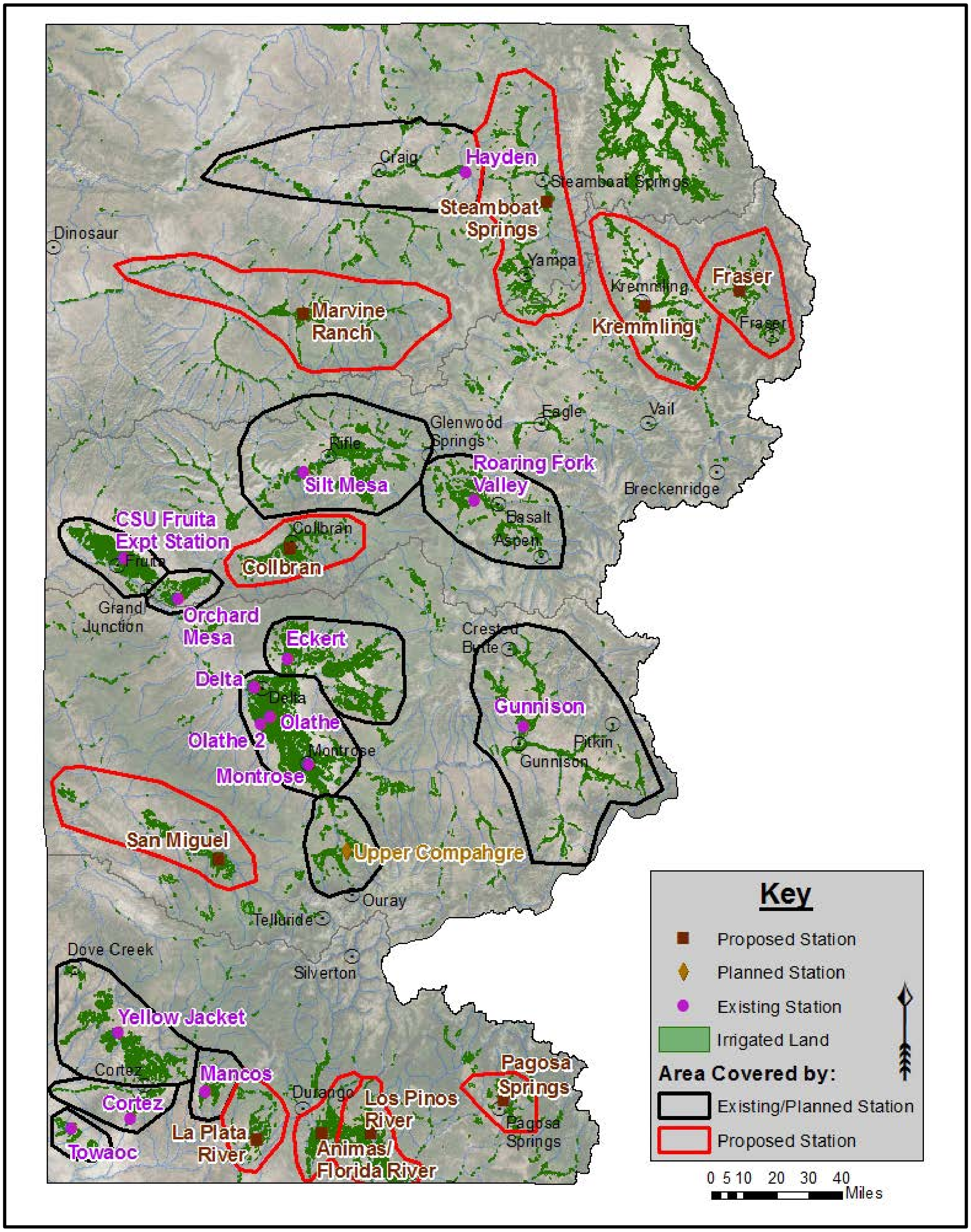


Figure 2-3 Colorado extended climate stations and estimated coverage

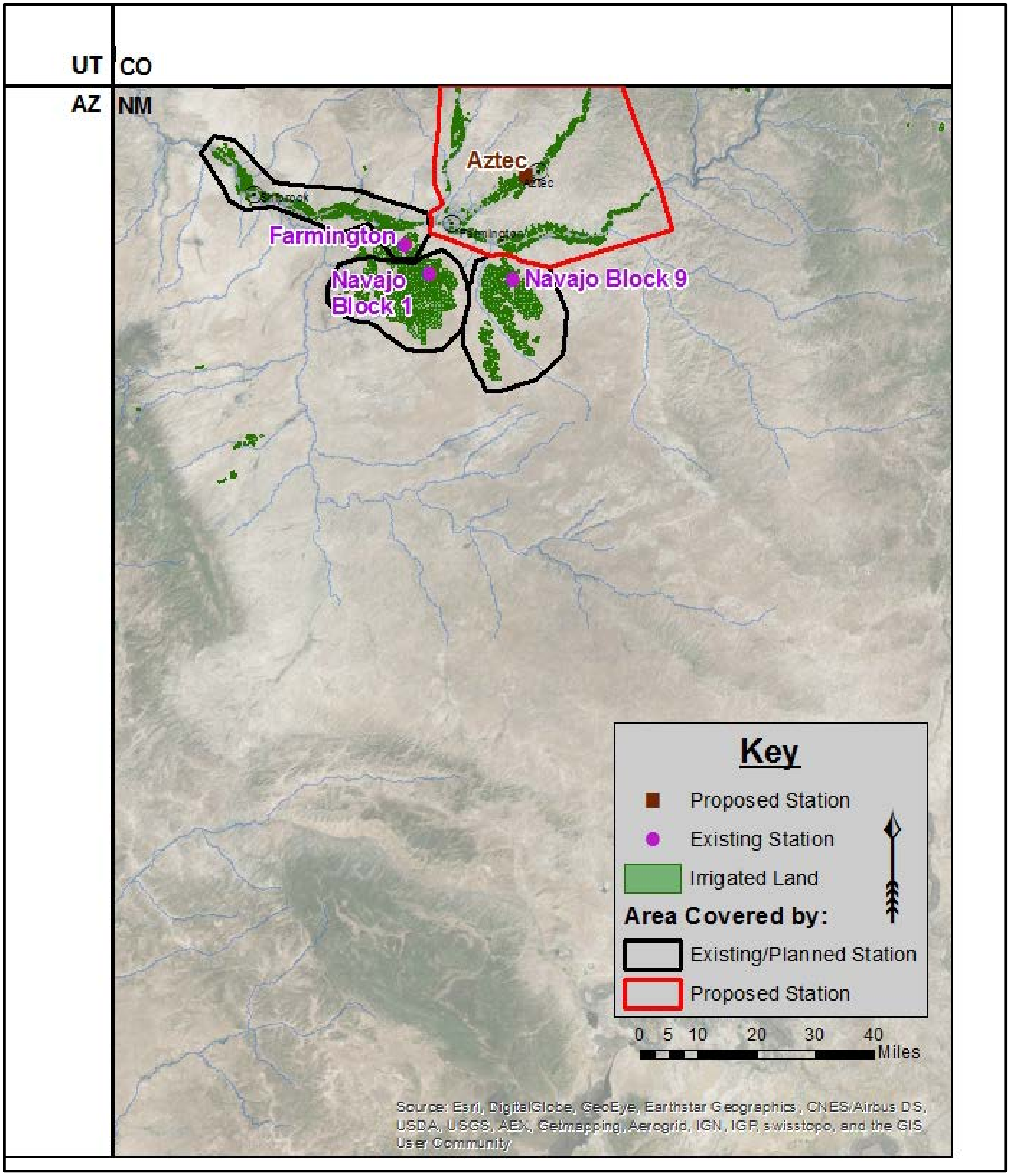


Figure 2-4 New Mexico extended climate stations and estimated coverage

There are existing networks of Extended Climate Stations and network coordinators with expertise in selecting equipment, installing, and maintaining those networks in the UCRB. However, there have been few EC towers installed and operated. Therefore, this section provides much greater detail on properly selecting locations and equipment and assuring that equipment is properly maintained.

3.1 BACKGROUND

Evaporation measurement and estimation has a rich history of innovation in instrumentation and methods. ET measurement techniques can be broken into three categories: 1) methods based on conservation of energy, 2) methods based on conservation of mass, and 3) methods based on the physical transport process. For a more complete treatment of evaporation measurement history and a discussion of a broad array of techniques, see *Hydrology: An Introduction* (Brutsaert 2005).

Energy balance techniques typically assume that the land surface energy budget is closed with four potential energy flows: the total available (net) radiation, R_n; the heat conducted to and from the soil, G; the total sensible heat transported into the air, H; and the latent heat, λE, associated with the vaporization of water (i.e., ET). The team neglected the terms of photosynthesis, energy stored in the canopy, and horizontal advection which are generally less than 2 percent of the total energy balance under uniform field conditions (i.e., within the error of measurement of the other terms in the energy balance). Energy balance approaches measure R_n, H, and G to find the ET as a residual. For this Project, Penman-Monteith and remote sensing techniques based on SEBAL (Surface Energy Balance Algorithm for Land) fall into this category.

Mass balance techniques typically measure water storage directly, including soil water, irrigation and/or rainfall, runoff and stream flow, and deep percolation below the root zone (groundwater). Change in storage can be used to determine ET as a residual term. Consumptive water use is a necessary input for these types of field methods, making them inappropriate for this Project, where consumptive water use is the variable to be measured. This category has one notable technique, lysimetry, which is one of the most accurate, precise, and direct measures of ET.

Physical transport methods monitor the mechanism that is responsible for the movement of water through the environment. Sap flow techniques monitor the total transport of water through the stems of large plants (typically trees). Flux chamber techniques isolate a portion of the land surface from its surroundings and monitor the response. EC monitors the vertical advection of water vapor from the land surface by atmospheric turbulence. These methods each have a unique mathematical foundation with concomitantly unique assumptions and simplifications. This report is focused on the EC technique as a method to measure the evaporation from a relatively large land area.

EC has been widely used and discussed in literature and many excellent reviews exist (e.g., Baldocchi 2003; Lee *et al.* 2006). EC has been applied to measure mass, momentum, and energy fluxes in many different environments such as over agricultural crops (Soegaard *et al.* 2003), forests (Baldocchi *et al.* 2001), and snow-covered regions. EC measurements of the trace gases of carbon dioxide (CO_2) and water (Baldocchi *et al.* 2001) have become extremely common, but measurements of other trace gasses of interest are also possible (e.g., methane and nitrous oxide fluxes) (Smeets *et al.* 2009). The underlying measurements of wind velocity and gas concentration are typically made at a relatively high sampling frequency (e.g., 10 Hertz [Hz] or greater) using closed-path or open-path measurements of the gases of interest. Open-path systems sample the gas directly at the sensor head, while closed-path instruments require a pumping system that acquires a gas sample and transports it to a bench-top gas analyzer. This high frequency sampling is necessary to capture the full range of motions responsible for gas movement by atmospheric turbulence. High frequency signals are then processed to provide measurements of ET on a 20- to 30-minute interval. See Appendix C for a description of the mathematical foundations of the technique. The major assumptions of the technique are presented below.

3.2 ADVANTAGES AND SYNERGIES OF EC

A robust experimental design will compare methods from different categories, as they rely on independent sets of assumptions and mathematical analyses. EC provides an independent measurement not based on the same set of fundamental assumptions employed by the other ET estimation techniques used in this Project. That is, SEBAL-based satellite techniques and Penman-Monteith are based on conservation of energy and EC is based on turbulent transport. EC has emerged as the current standard for field-based ET measurement. EC is the backbone of flux estimates for both the Ameriflux network and the new NEON network. There is a 30-year history of its successful use in the field. Within the category of physical transport methods, the EC method has the advantage of taking representative measurements of a larger land area. EC measures a weighted average ET from an area defined by its measurement footprint (see Section 3.7). This area varies in time, depending on atmospheric conditions and instrument height above the land surface. Instruments located at greater heights will have a larger footprint. Typical footprints for a 30 feet tower are greater than 0.25 acres in area. By contrast, sap flow and chamber techniques are limited to areas of extent on the order of 10 to 100 square feet (ft^2).

A comment on disagreement of energy balance and EC: The discordance between the underlying physical assumptions of ET techniques can also lead to discordance between the measurements. Lack of surface energy budget closure is a common issue raised in conjunction with EC flux measurements. That is, if the four major energy transport pathways (that are the basis for energy balance techniques) are measured independently with EC and other specialized instrumentation, there is typically an amount of available energy (from the sun) which remains unaccounted (see Wilson 2002 and the references within for a detailed analysis). The portion of energy that is missing in this budget is between 5 and 20 percent of the total net radiation, R_n. That is, EC techniques tend to give evaporation measurements that are *less* than those given by energy balance techniques. There has been considerable debate in the literature as to the significance of the disagreement between EC and energy balance techniques, and some careful analysis (Higgins 2012) and experimentation have begun to close the gap in reported evaporation values and understanding. Higgins' assessment (2012) is that the disagreement centers on the formulation of the energy balance equation itself; that there can be additional, unmeasured transport pathways of energy (e.g., storage of heat in the soil, and plant mass and advection of heat and water vapor in the lateral directions). These transport pathways are not necessarily captured by the EC method, while energy balance methods lump energy transported through these pathways into the ET estimate. Regardless of where one stands on the issue, it is pragmatic to recognize that different methods each have their own strengths, assumptions, and treatment of the physical process. This leads to potential mismatches that can be understood and interpreted.

3.3 ASSUMPTIONS OF THE EC METHOD

1. Turbulence is responsible for the majority of the gas transport. The rapid sampling of the velocity vector allows for investigation of the velocity energy spectra. Thus, this assumption is verifiable by analysis of the acquired data. If the energy spectra of the velocity exhibits an inertial range with a -5/3 slope, this assumption is likely satisfied.
2. The land surface is flat and homogeneous. This assumption is the most restrictive, but EC has been used successfully in a variety of environments where this assumption is not satisfied strictly. The most fruitful path forward is to carefully select measurement locations where this assumption is most likely to be met. For example, agricultural fields tend to be planted with a single crop, and therefore satisfy the homogeneity portion of this assumption. Therefore, relatively flat agricultural fields should be chosen.
3. The mean vertical wind is assumed to be zero. Again, the underlying data can be evaluated to determine if this assumption is satisfied. The mean vertical motion in the atmosphere should be zero as a consequence of mass conservation in a flat and uniform field (see Assumption 2 above). If this assumption is violated, it is likely that the instrument was not installed parallel to the ground surface. Such a disagreement is not fatal as the frame of reference of the data can be rotated. This is a typical data handling 'correction' that is applied.
4. Stationarity is assumed. That is, the running mean of the humidity does not change appreciably within the period of flux calculation. One typical check is to fit a linear trend to the humidity data. If the slope is above a threshold (could be zero), the trend from the data can be removed with little loss in flux quality.

This discussion reveals that, of the four major assumptions, only the first two can disrupt the measurement technique. Assumption 1 can be violated at times of extreme flow quiescence and atmospheric stability. These events typically occur in the overnight hours. As we are interested in the consumptive water use by active plants, for which the vast majority of the water use occurs in the daytime hours, this assumption is likely to be satisfied during the times of most interest for consumptive water use monitoring. Assumption 2 is a key consideration for EC tower siting, as an inappropriate EC tower location can produce less reliable results.

This section is intended to provide an introduction and practical guidance on the subject of EC, tower setup, maintenance, and data handling -- an exhaustive description would require hundreds of pages (and there are excellent compilations on the subject).

3.4 RECOMMENDED READINGS FOR GREATER DETAIL

The following readings are recommended to ascertain additional detail on EC, and surface flux measurement and analysis.

1. Aubinet, T. Vesala, and D. Papale. 2012. Eddy covariance: a practical guide to measurement and data analysis. Springer.

   Commentary: If only one book is to be chosen, choose this one. It is complete in both theory and practical considerations

2. Lee, X., W.J. Massman, and B.E. Law, Eds. 2006. Handbook of micrometeorology: a guide for surface flux measurement and analysis. Springer Science & Business Media.

Commentary: Also complete, but not as recent and focused more on scientific applications. This one may have better insight for running networks of towers.

A detailed description of the infrastructure required to perform these measurements is provided in Section 3.5. A description of the data handling, corrections, and QA techniques is presented in Section 3.6. Section 3.7 discusses the flux-footprint and Section 3.8 makes recommendations for preferred qualifications of personnel. The data from the 2015 field measurement campaign is presented in Section 3.9. Finally an analysis of the UCRB for future EC measurements is presented in Section 3.10.

3.5 INFRASTRUCTURE

3.5.1 Sensors

Appendix D contains manufacturer information of open path instruments like the type pictured on Figure 3-1, and information on the range of manufacturers that provide suitable and anemometers.

1. **A fast response humidity sensor**. This device must be able to measure the moisture content of the air with a repetition rate of at least 10 Hz (20 Hz is preferred). The currently available instruments rely on infrared absorption of light across a path of known distance.
2. **A fast response three-dimensional (3-D) anemometer**. This device must record the three components of the wind velocity vector with a repetition rate of at least 10 Hz (20 Hz is preferred). The currently available instrumentation relies on measuring the time of flight of acoustic pulses across a domain of known size.

   Sensor geometry plays a role in data quality analysis. Due to the mounting configuration and support structure of the instrument, there are some wind angles of attack which may yield data of lesser quality. This is the so-called “tower shadow effect.” The Campbell model is most impacted in this regard. The Campbell model also has some of the most desirable specifications. These units also span a range of price points. Thus, typical wind conditions on site, accuracy requirements, and price point would together determine the most suitable unit. An important item to consider is that the Licor LI7500A does not work well with the Campbell Scientific equipment and vice-versa due to their data logger requirements (i.e., Licor uses Ethernet, Campbell uses SDM [Security Device Manager] addressing). If a LI7500A is chosen for vapor concentration measurements, one should not choose a Campbell Scientific anemometer.
3. **A data-logging solution**. Data from the instrumentation must be acquired for later analysis. The logging solution for EC must be matched with the choice of sensors and their communication protocols. That is, the choice of the fast response humidity sensor will determine the appropriate logging solution.

   The fast response hydrometer and the 3-D acoustic anemometer must be placed in close proximity, though not too close as to create flow distortion effects, although some flow distortion and tower shadow is inevitable for sensor pairs. Since the choice of the humidity sensor constrains the choice of acoustic anemometers and data logging solutions, only two potential sensor systems are presented: one based on the Campbell scientific IRGASON, and one based on the Licor LI7500A.

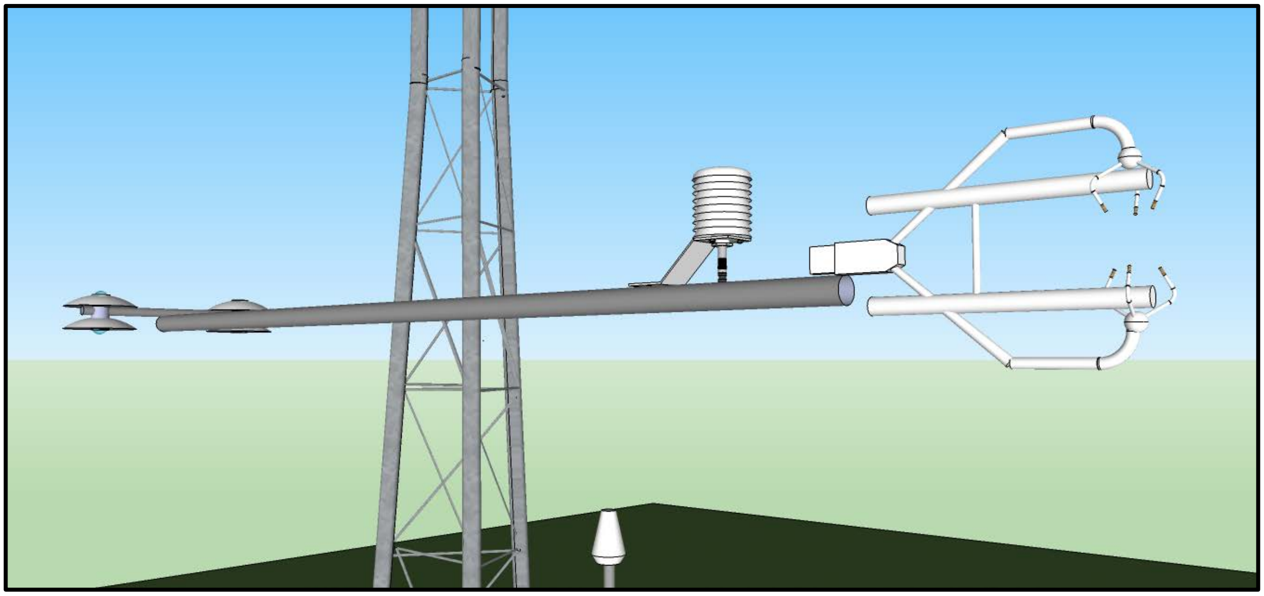


Figure 3-1 Close-up schematic of the main sensor package

Sensor and Logging Package #1

The total cost for an integrated IRGASON sensor with a CR6 data logger is $22,225 (see Appendix E for a current price quote). This price includes a fast response humidity sensor that is fully integrated into a CSAT anemometer. All of the required software, cabling, and other ancillary equipment are included in this price (though no replacement parts are included).

Replacement parts would be the same cost as the original parts. Having backup parts is a reasonable precaution if there is more than one EC tower. Lead times on instrumentation purchases and repairs that involve the manufacturers vary from three to six weeks (it would be a management decision to decide if such a window is an acceptable loss if something was to malfunction seriously). Otherwise, backup instruments can fill this gap while repairs take place. The extra cost would cover an unforeseen data gap due to catastrophic failure where the gap could be up to six weeks (or about 25 percent of a growing season).

Figure 3-2 illustrates the deployment of a flux station with a 3-D sonic anemometer/thermometer and an open-path infrared gas analyzer. The unit pictured is the Campbell Scientific IRGASON.

Figure 3-2 Campbell Scientific IRGASON

Sensor and Logging Package #2

The total cost for a LI7500A with a Gill sonic anemometer and Licor logging system is $27,570 (see Appendix E for a current price quote). This price includes all of the software, hardware, cabling and ancillary supplies (though no replacement parts are included). Figure 3-3 is a LI7500A with a Gill anemometer representing sensor and logging package #2.

Figure 3-3 LI7500A with a Gill Anemometer

Discussion of the Primary Sensor Package Selection

The Campbell unit has an advantage on price and integration. The integrated nature of the Campbell package eliminates a data handling and QA test, the so-called "sensor separation correction." The Licor package has integrated satellite communication that reduces the price-gap somewhat, and the geometric configuration of the Gill has a smaller sector of wind angles of attack that are tied to flow distortion (i.e., the flow distorted by the wake of the LI7500A) (which ultimately depends on the relative positioning of the Gill and the LI7500A). The Licor system is also compatible with the manufacturer's EddyPro software which may reduce data analysis costs. At the time of this writing, the Study Team had not tested the Licor software solution.

Figure 3-4 shows the schematic of a tower installation (traditional mast) with the fencing and power system depicted.

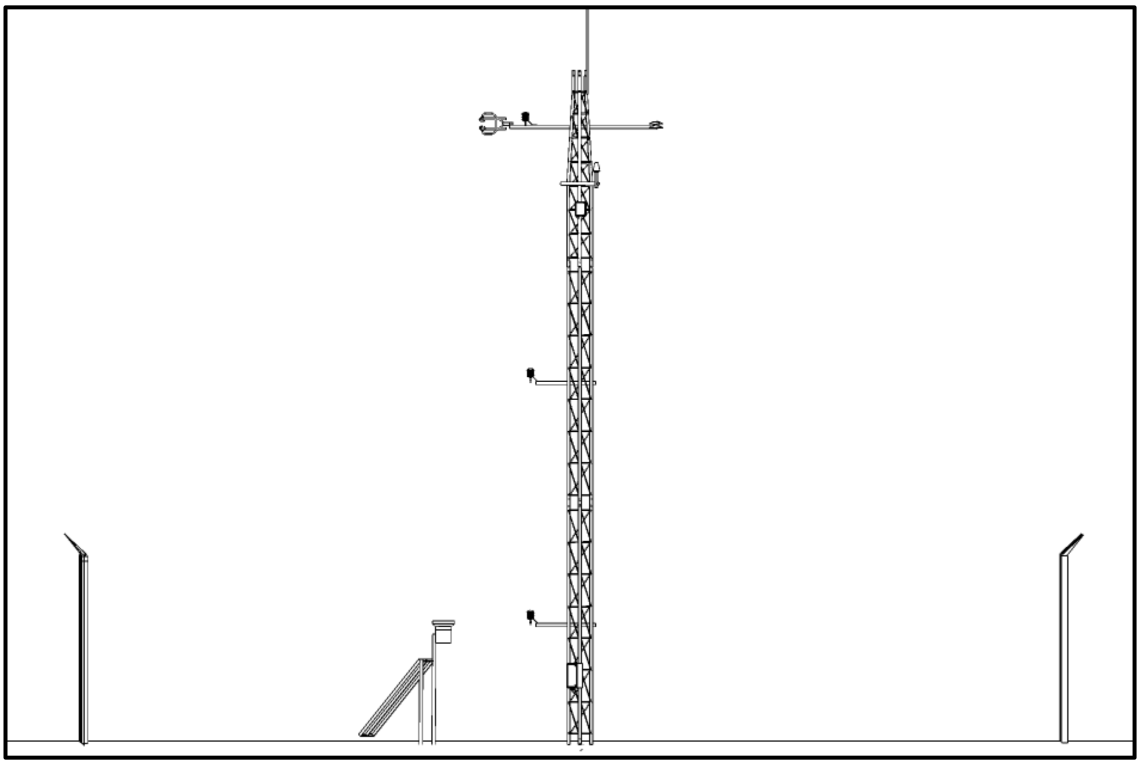


Figure 3-4 Schematic of an EC tower installation (traditional mast)

Additional Sensors (Optional)

1. **Solar radiation, preferably the net radiation**. With an additional solar radiation measurement, the raw EC measurements can also be used to compute the Penman-Monteith ET estimate which can provide a cross-check of the EC results. Net radiation also provides an independent measurement of one of the components of the surface energy balance. The typical net radiation sensors cost approximately $2,000.
2. **Ground heat flux, (only if net radiation is measured)**. The full surface energy balance computation can be calculated when this instrument is also included. A check of the energy balance closure provides a valuable cross-check on data quality. The typical cost of a ground heat flux plate is approximately $600.

3.5.2 Physical Infrastructure

A support structure is required to suspend the instrument above the land surface. The sensor systems require electricity and should be protected with fencing. Consideration should be given to the local wildlife, and a lightning rod and proper grounding should be used.

1. **Tower structure**: There are two classes of tower structures: walk-up towers and traditional masts. Walk-up towers resemble scaffolding systems and have a wide base that contains a ladder or stair system. These systems have a greater impact on the local atmospheric flow, but are easier to climb and maintain. Typical masts are less than 20 inches wide, and may be more challenging to climb. A permanent tower installation would benefit from a concrete base. Total costs, safety, and data quality considerations should be considered when choosing a support structure. The cost of tower structures range from $1,500 to $10,000.
2. **Hardware**: The tower will be secured by a set of guy wires and associated hardware. Hardware costs are $500.
3. **Electricity**: The electrical system should be given full consideration. The most common reason for data gaps and data loss is interrupted power. Nearly all of the sensors and logging solutions will be powered by 12-volt DC. Line power (a wall plug) is the most reliable, but may not be available at the majority of measurement locations. Solar power is a reliable alternative, provided the power system is designed with an appropriate factor of safety. That is, the battery reserve should last several days without recharging, and should be able to be recharged fully in less than one day. An appropriate charge controller is needed, and the data logger program should monitor the battery voltage to determine if there is a persistent problem with the power system. More exotic power systems are also available for places with low light conditions (e.g., generators, fuel cells, etc.), but these require more maintenance. Electricity costs are $1,500.
4. **Lightning protection**: A lightning grounding kit should be electrically insulated from the tower and properly grounded to its own ground. In addition, all sensors and loggers should be electrically isolated from the EC tower and properly grounded to their own separate ground. This is unlikely to save the instruments if the EC tower experiences a direct lightning strike, but it does provide some protection from nearby strikes. Lightning protection costs are $800.
5. **Fencing**: The EC tower location must be enclosed in fencing to keep unauthorized personnel from climbing or otherwise disturbing the EC tower, and to reduce the chance that large local wildlife or domestic animals (e.g., livestock) impact the measurements. The estimated costs for fencing range from $1,000 to $3,000.
6. **Cable protection**: The completely assembled system will have many assorted wires and cables for data and power transmission. Any of the cables that are near or touching the land surface should be encased in electrical conduit to protect them from rodent damage. The typical cost of cable protection is $50.
7. **Wildlife management**: All gaps in electronics enclosures should be filled to reduce access by rodents. Bird-scare tape may help deter nesting, but raptors may still nest or perch. Insect nesting can also cause issues, but is rarer. In this Study Team's experience, a pliable plastic substance (like silly putty) has outperformed other alternative approaches. The total estimated cost is $20 for the wildlife management techniques described here.

3.5.3 Telemetry

There is limited local disk storage space on all data acquisition systems. If there is no real-time telemetry of the raw data: 1) there is no way to know if there is a problem with the installation without a site visit, and 2) the only copy of the data is on the logger until a technician performs a back-up during a site visit. Thus, reliable telemetry is necessary and can reduce the total number of site visits and the risk of data loss. The preferable configuration would provide a live stream of the 20-Hz data to the data analysis expert. With this configuration, problems could be detected immediately and repairs carried out in short order. A live feed would also reduce the chance of catastrophic data loss (due to unforeseen electronics issues or other unpredictable events). Due to the data volume, a local Ethernet or wireless internet connection would be the most sensible option to transmit the 20-Hz raw data. The best option for a permanent site is therefore to install Internet service along with power utilities. Such an investment would result in far superior reliability and robustness. If this investment is not possible, compromises can be made. Rudimentary flux calculations and systems diagnostics can be done with the data acquisition system. The results from these computations can be sent easily by cell, satellite, or radio communication. In this way, a flux data analysist would be able to ascertain if there was a problem with the EC tower and/or equipment, but the raw 20 Hz signal would have no backup unless a technician is dispatched in regular intervals to perform this task. Depending on the cost of an EC tower service visit (which would include technician time plus travel time), it may be more economical to have a real-time stream of the 20-Hz data via the Internet. Without full telemetry for the 20-Hz data, a technician should be sent to the site once per month, at a minimum. If the travel and labor costs for one EC tower visit per month are greater than the monthly cost of full telemetry, it is economical to install the local Internet connection. The estimated costs for the initial install of the telemetry system is $2,000 and then $100 per month for service.

3.5.4 Site Survey

A survey of the immediate area surrounding the EC tower should be performed at the time of setup. Major land features, cropping patterns, fence lines, land classifications, etc. should be noted and catalogued. The survey is done to cross-check the assumption of a homogeneous land surface (in conjunction with the EC tower footprint), and is a necessary part of the metadata to describe the site.

3.5.5 Tower Maintenance

Recalibration of the sensors and the loggers should occur on a per annum basis. The infrared gas analyzer may require more frequent calibration (as determined by inspection of the signal and error reports). Calibration of the infrared gas analyzer can be done in place with a portable calibration sleeve, and a set of standard gasses: dry nitrogen, CO_2 at a known concentration, and humid air at a known dew point. Dry nitrogen and standardized CO_2 gasses can be purchased in cylinders. Air at a known dew point is typically made with a dew point generator (e.g., Licor instruments, which costs approximately $8,000). Only one of these devices is needed for a large number of EC towers. Logger calibration and sonic anemometer calibration is typically performed by the manufacturer yearly at a cost of approximately $500 per instrument per calibration.

At least once per year (though preferably during each site visit), wires should be checked for any fraying or loose connections, humidity indicators should be checked within electronics enclosures, and desiccant packs replaced as needed. The power system should also be regularly maintained and the battery charge should be monitored. If solar is used, the vegetation around the panels should be kept short to keep the panels in full sun.

Both Campbell Scientific and Licor have recommended maintenance practices in their manuals for their infrared gas analyzer. Each system has an oxidizing agent within the housing of the sensor head that should be replaced on an interval specified in the manual (approximately yearly). In addition, the laser system has lenses that should be cleaned if the signal strength falls below a predetermined threshold (e.g., 70 percent for Campbell EC150). These maintenance procedures could be performed easily during the winter (off) season for this Project.

3.5.6 Tower Location within the Field Site

Preliminary meteorological measurements should be performed before EC tower installation to determine the predominant wind directions during the daytime hours. The site should be assessed to determine which areas would represent the most homogeneous upwind field conditions. The EC tower should then be placed downwind of the most relevant portion of the field under investigation (as determined by the preliminary meteorological data).

Tower shadow, sometimes called the wake region, is the set of wind directions which arrive from the aft of the instrument, or in such a way that the upwind turbulence is disturbed by a tower's or sensor package's wake. Sensor and EC tower positioning decisions should be made with this in mind. Most field locations contain discrete elements that are undesirable for flux measurements. These areas are usually homes with driveways, roads, or other access pathways. If possible, it is best to orient the sensors relative to the EC tower and each other such that those undesirable areas fall within the tower shadow. If the site does not have problematic elements, then the sensors should have a relative orientation such that the tower shadow is aligned with the least common wind direction (see Figure 3-5 for an example).

On Figure 3-5, data for wind directions from the EC tower side of the Campbell Scientific IRGASON are impacted by the wake of the tower. The typical practice is to discard the data that falls within this sector (the so-called "tower shadow") depicted by the red area in the plot on this figure. The location of this area is determined by the relative position of the instruments and tower (the yellow object at the center of the image). Efficient setup places the tower shadow sector in the least common wind directions or in an area where flux measurements would have less meaning. In this example, the tower shadow was placed to cover a nearby house and small valley which also coincide with the least common wind directions. This sector also contains a field that was green during August and September, when the field to the north of the EC tower was not. The limitation of the instrument is that evaporation measurements must be excluded from this region (approximately 12 percent). (Note that in future comparisons with remotely sensed data, only measurements outside of the EC tower shadow were used.)

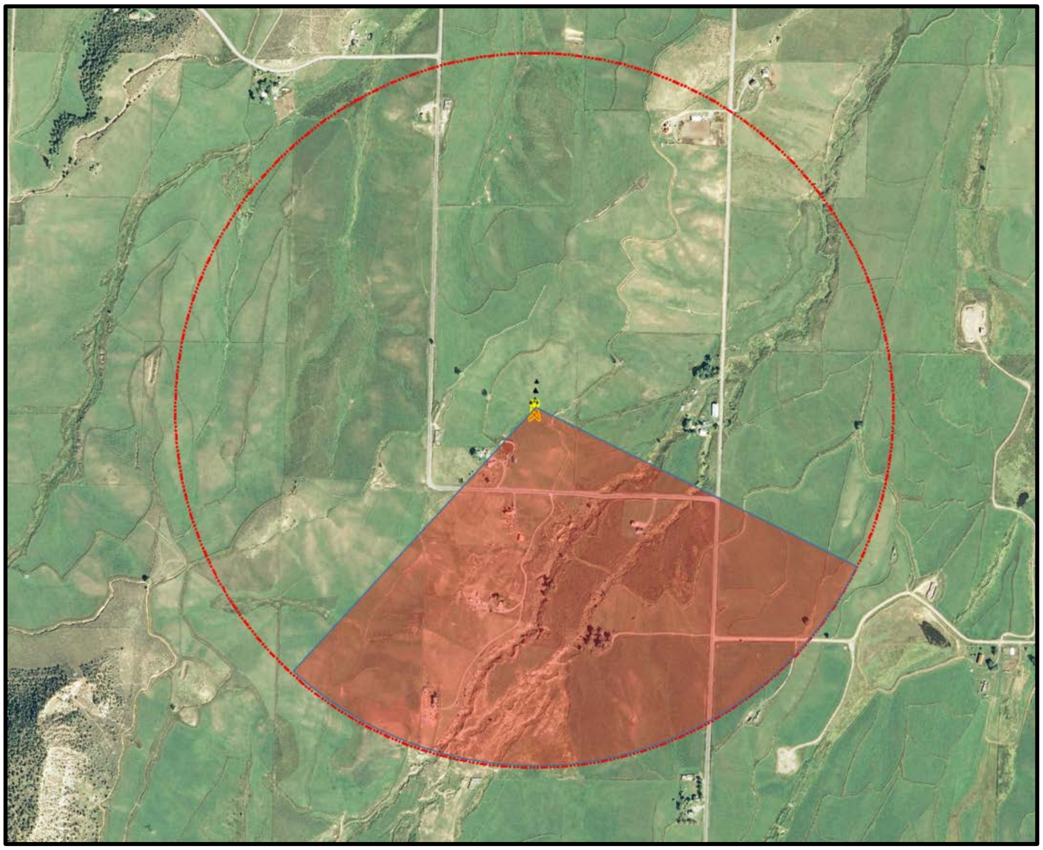


Figure 3-5 Sensor orientation and EC tower shadow example

3.5.7 Safety

Field measurement in an agricultural environment does include several safety hazards that should be discussed and addressed prior to fieldwork. All personnel should have appropriate safety training for the tasks they are assigned. There are tower climbing certifications and safety procedures for licensed tower operators that are available. Ground crews should wear personal protective equipment (e.g., safety glasses, gloves, steel-toed boots, and a hard hat at minimum). An appropriate risk management/safety plan should be developed and consultation with a safety expert is recommended as this section just hits on the safety considerations and does not account for all safety hazards, concerns, or field scenarios that may be experienced.

3.5.8 Lessons Learned and Potential Failure Modes

Care, proper planning, and engineering can reduce the chance of data loss. Following are some recommendations to address the various failure potentials based on past experiences and lessons learned.

1. **Power failures**: Risk of power failure can be reduced by designing a robust power system that has redundancy.
2. **Lightning strikes**: The effects of lightning strikes can be mitigated by installing lightning rods and independent grounding; however, even with such measures, a direct lightning strike would still likely result in sensor loss.

3. **Electronics failures**: Constant monitoring of the system outputs through telemetry can reduce the potential for data gaps that result from electronic failures.
4. **Wildlife interference**: Fencing helps keep large animals out and conduits help keep small animals and rodents from chewing wires. Insect repellant can be utilized to keep nesting insects in check, and bird scare tape can reduce the presence of perching birds.
5. **Vandalism**: Fences and appropriate signage to explain the intent of the EC tower help reduce the potential for vandalism. Placing patriotic imagery on the signs has historically had an additional positive effect in discouraging vandalism.
6. **Falling trees**: To reduce the risk of falling trees damaging the EC towers, the towers should be installed away from tall trees and in clear areas, if possible.
7. **Extreme weather**: The acoustic anemometer does not function in extreme weather conditions (e.g., very high winds or excessive precipitation). As such, the system will not return fluxes at these times. At the time of this writing there are no known solutions to address extreme weather issues (it is a limitation of the instrumentation).

The total costs for EC tower installation and continuing operation are reflected in Table 3-1.

Table 3-1 Cost estimate for EC Towers[1]

	Initial Costs	**Initial Labor**	**Reoccurring Costs**	**Reoccurring Labor**
Sensors	$27,000			
Infrastructure	$8,000			
Hardware	$1,000			
Telemetry	$2,000		$1,200/year	
Consumables			$1,000/year	
Calibration			$1,000/year	1 person-day/year
Installation		10 person-days		
Site Survey		1 person-day		
Site Maintenance				12 person-day/year
Data Analysis				0.2 FTE

Note:
[1]Assuming a technician pay rate of $100 per hour, and including benefits and a 20 percent contingency, an EC tower will cost approximately $55,000 to purchase and install, and will require approximately $16,300 per year to maintain. This estimate does not include the cost of data analysis.
FTE = full-time equivalent

The typical life of an EC tower and associated equipment/sensors/etc. with proper maintenance is approximately 10 years (this is a conservative estimate).

3.6 DATA HANDLING AND ANALYSIS

The EC system will output the sonic temperature, a measure of the moisture content of the air, the CO_2 concentration, the three components of the velocity vector tensor, and a set of diagnostic flags (usually two) at a sampling rate of 10 to 20 Hz (user selectable). This corresponds to eight measured variables that are sampled 20 times per second. The system operates continuously to create several gigabytes of data per month. This rate of data production is well within the capabilities of modern computing, but does require specialized handling and archival procedures. It is recommended that a centralized server, with regular backups, is used for archival.

The raw data in itself requires multiple processing steps to determine the ET. Automated software is available to carry out these functions. See EddyPro (https://www.licor.com/env/products/eddy_covariance/eddypro.html?gclid=CPvivufDmskCFYVhfgod_6wPOA) or EdiRe (http://www.geos.ed.ac.uk/abs/research/micromet/EdiRe/EdiRe). These steps can also be implemented in a programming environment of convenience to the user (e.g., MATLAB, R, and Python are the most common). For example, the analysis presented in Section 3.9 was prepared in MATLAB with code developed by Higgins (2012). Regardless of the approach, it is important that the user understands the reasoning for each step as it relates to the quality of the final product, the unique physical characteristic of the site, and the chosen instrumentation. An estimate for the total person hours to accomplish one year of data analysis is 400 person hours; assuming $100 per hour (which includes wages and benefits), data analysis is estimated to cost $40,000 per EC tower per year.

3.6.1 Data Analysis Steps

The following is an overview of the data analysis steps.

1. **Initial Screening:**
   a. **System-generated error flags**: The EC system can be programmed to output a series of self-diagnostics associated with each measurement. These typically take the form of an error code that is tied to a specific problem. For example, if the power supply voltage drops below a critical threshold, the quality of the data output becomes suspect, and a diagnostic flag is generated. Unexpectedly low signal strength can also trigger a diagnostic flag. Such triggers are usually associated with heavy precipitation events. Historically, practice is to remove all data that are suspect, and typically, 10 to 20 seconds of data in the time series adjacent to segments of continuous error flags are also removed.

   b. **Determining any regions of disturbance (tower shadow)**: The manual of the CSAT3 includes a recommendation that the sector of wind directions that are aft of the instrument be removed from analysis. This sector is defined as the 120 degrees directly to the aft of the instrument head (see Figure 3-5 above for a visual representation). All measurements that occur when wind is arriving from this sector are removed from the analysis. Thus, EC tower and instrument placement is critical relative to predominant wind conditions. To maximize the return of useable data, the regions of disturbance (tower shadow) must be placed such that they fall within the sector of least common wind approach directions.

   c. **Check for realistic values**: A physical constraint test should be performed where temperatures are checked against long-term mean values; the humidity should not be above 100 percent, and the wind speed should be within the stated measurement range of the instrument. Such errors are uncommon and may indicate that the instrument requires calibration if the problems persist. Another check that should occur at the same time is a check to determine if there are condensing conditions (i.e., the temperature approached the dew-point). Condensation on the laser lenses can disturb the measurement, but most modern systems have heating elements to reduce this problem.

2. **De-Spiking**: It is common for the raw signal to contain infrequent large spikes and instrument dropouts at a single moment of measurement. These events are typically caused by natural interference of the sensor's operation. An insect or plant matter passing through the sensor's control volume will cause a single spike (at least) or perhaps a lost data point. Several methods exist to de-spike the data. Perhaps the most accepted approach by the community is described in *Quality Control and Flux Sampling Problems for Tower and Aircraft Data* (Vickers and Mahrt 1997). For example, the standard deviation of the data under consideration is calculated, and data that fall outside a certain threshold (typically five standard deviations) are considered as spikes and eliminated. See Figure 3-6 for a graphical representation of an un-treated data stream being de-spiked.

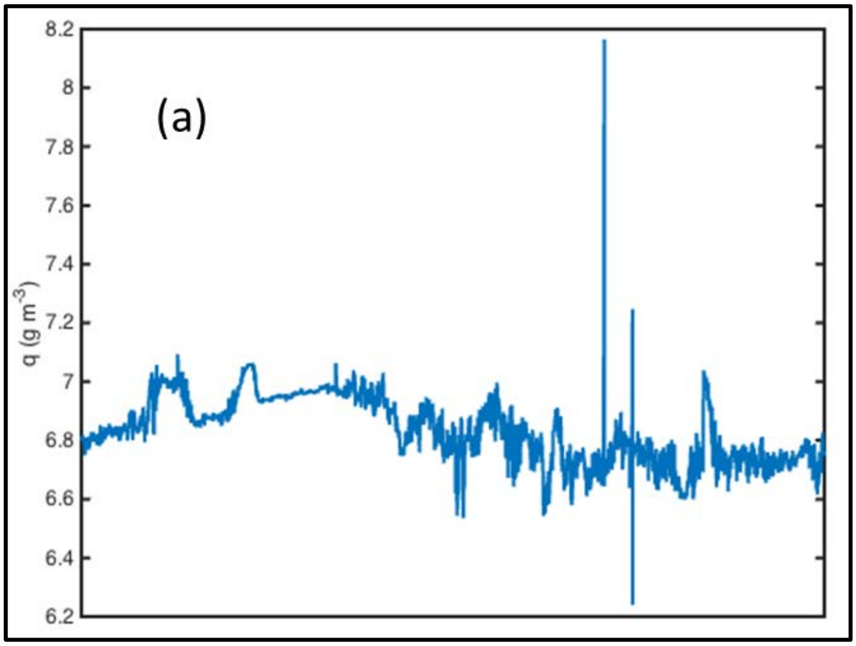
3. **Density corrections**: The density of air is impacted by its temperature and admixture. Small changes in density can affect the resulting ET measurement, especially in arid environments where the total ET is relatively small. This is corrected by the procedure outlined in *Correction of Flux Measurements for Density Effects Due to Heat and Water Vapour Transfer* (Webb *et al.* 1980).

4. **Planar fit (or other rotation methods)**: To compute the EC, the fluctuations of the vertical velocity component need to be isolated. This step endeavors to rotate the frame of reference of the data such that the mean of the cross-stream velocities are zero. This is not a correction of the data, as the data are not changed but are merely expressed in a newly defined coordinate system. If the instrument is not installed perfectly parallel to the land surface, or if the EC tower is installed above a land area with significant curvature, the average of the vertical wind may depend on wind direction. This procedure is outlined in detail in *Sonic Anemometer Tilt Correction Algorithms* (Wilczak *et al.* 2001).

5. **Ogive analysis**: This analysis is performed to determine if the averaging interval is of sufficient length. Specifically, this function is proposed as a test to check if all low-frequency motions are included in the turbulent flux measured with the EC method (Foken 2008). The ogive is the cumulative integral of the co-spectrum starting with the highest frequencies. The timescale where the ogive asymptotes to a constant value is the shortest possible segment length.

6. **Break data into averaging intervals**: In this step, the data are broken into intervals. These interval lengths cannot be too short, lest there be non-convergent statistics (checked in step five), nor can these intervals be too long, lest there be a violation of the stationarity assumption within the EC theory. Typical time intervals are 20 to 30 minutes. The analysis hereafter is to be performed for each segment individually.

7. **Block de-trending**: The calculated EC is impacted by long-time scale changes in the atmosphere that are not responsible for the transport of water vapor. These are the so-called non-stationary elements of the atmospheric boundary layer that can be caused by large wave-like motions or the persistent change of the diurnal cycle. Often these changes occur on timescales that are significantly longer than the averaging interval for a single flux calculation. For each segment and every variable, the linear trend with respect to time is removed (see Foken 2008 for more detail).



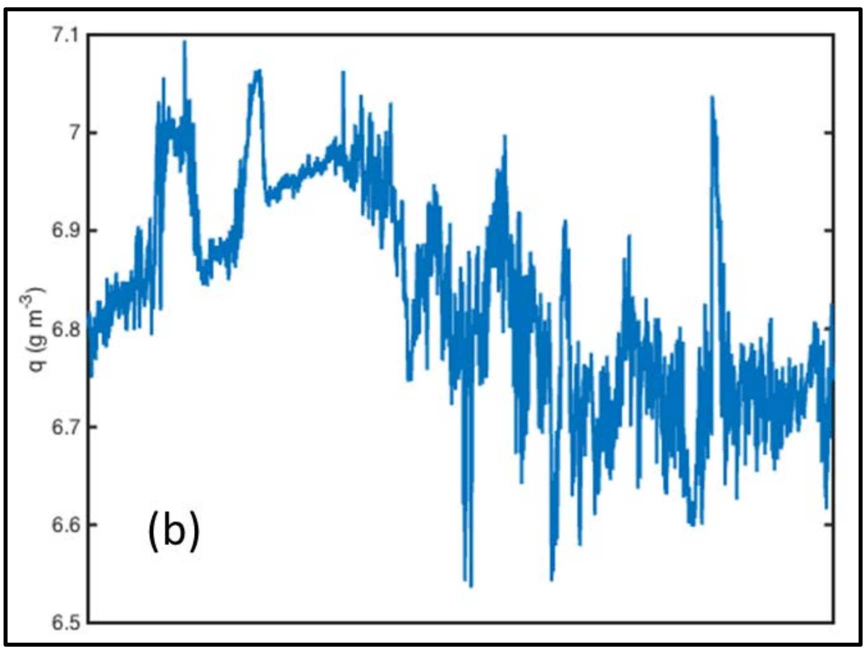


Figure 3-6 An un-treated data stream (a) and de-spiked data stream (b)

8. **Optional spectral analysis**: The power spectral density of each segment can be plotted and inspected to determine if there is inertial subrange. The objective is to ascertain if the spectra contain a segment with a slope of -5/3 on a log-log plot. The presence of this region indicates that there is a significant amount of turbulence to apply EC. For daytime measurements (as is the central theme of this report) this condition is almost always met.
9. **Flux calculation**: Compute the EC between the humidity fluctuations and the vertical wind component for each segment.
10. **Additional flux corrections**: There are many situation-dependent flux corrections that can be applied if desired. It is the Study Team's opinion that the importance of these corrections is relatively minor if appropriate experimental design, tower locations, instrumentation, and sampling is applied.
11. **Gap filling**: Data gaps are inevitable and must be filled and flagged to enable synthesis or integrative measures. Gap-filling is done to create integrals (e.g., monthly, weekly, yearly), and to make comparisons with other data or models. For example, satellite data may output the daily mean evaporation, or the cumulative evaporation over the season. It is important to indicate which portions of the data have been gap filled so QC metrics can be employed by those users who may need information at fine scales. Many elaborate gap-filling procedures are available, but perhaps the simplest is basic interpolation. For gaps on the order of an hour, the team linearly interpolated. Where gaps resulted because the instrumentation was done for longer than 24 hours, the team did not interpolate.

3.7 FOOTPRINTS

Fluxes that are measured are representative of an area surrounding the EC tower that varies depending on a number of parameters including tower height, surface roughness, and atmospheric stability. All of these parameters can be determined by a site visit and the high speed EC data stream. See Appendix C for an example of how atmospheric stability can be calculated.

EC measurements made in the inertial layer above the land surface represent an integrated measurement of fluxes from a larger area. It is therefore important to consider the "footprint" or region of influence of the flux measurement. A flux footprint is defined more precisely by Schmid (2002) as "the transfer function between the measured value and the set of forcings on the surface–atmosphere interface." For relatively simple topography and ranges of atmospheric stabilities, a number of analytical approaches for determining the footprint have been proposed (see Hsieh *et al.* 2000; Horst and Weil 1994).

The flux footprint is a function of wind speed and direction, surface roughness, and wind shear (related to buoyant stratification). Thus, the footprint for a single 30-minute data segment would be unique, and would change for the next segment as atmospheric conditions change. The footprint seen by EC instruments extends in the upwind direction, and is reduced with increased wind and instability. EC assumes a well-mixed flow representing a uniform contributing area; however, all real-world applications will occur in heterogeneous conditions. The weighted footprint function is used to attribute the measured flux to a weighted areal estimate (Göckede *et al.* 2006). The footprint model assumes that the land surface is a boundary condition (source/sink) for the water vapor flux. Many footprint estimation methods exist within the literature today that span a wide range of model complexity. Perhaps the most common is the model described by Schmid (1994).

This calculation is necessary to perform a direct comparison between an EC tower and a satellite ET method. That is, which pixels of the satellite scene correspond to the area where ET is measured must be known. For the data comparison, the footprint and associated pixels for each data interval was calculated and an average of the pixel data was computed to find the satellite-measured ET value to be paired with the EC ET value.

3.8 PERSONNEL

Operation, maintenance, and data stewardship of the EC method requires a specific set of skills. The most important skills include:

1. A working knowledge of a relevant computer programming language (e.g., C, Python, MATLAB, R).
2. Knowledge of statistics, preferably as they relate to atmospheric flows.
3. Experience with data loggers, data acquisition, and telemetry.
4. Experience building electrical and/or sensing systems.
5. Knowledge of database management.
6. Qualifications to perform field work (if personnel is performing maintenance as well as data analysis activities).
7. Appropriate safety training.

These skills are not commonly associated with personnel that possess a Bachelor's degree; therefore, the successful candidate would likely have a Master's degree or higher.

Some manufacturers provide targeted training for individuals who endeavor to become flux measurement experts. See https://www.licor.com/env/products/eddy_covariance/training.html for an example. The Study Team does not have firsthand knowledge of the effectiveness or applicability of these training programs.

A list-serve exists where flux measurement professionals post job listings. See http://fluxnet.fluxdata.org/community/opportunities/ for current listings. A job posting to this community site would likely result in a diverse pool of qualified candidates.

3.9 RESULTS FROM THE 2015 GROWING SEASON

A Campbell scientific IRGASON was deployed in an irrigated pasture south of the town of Silt, Colorado from April 1 to September 31, 2015. The EC system was operated at a sampling frequency of 10 Hz and acquired measurements of the three components of the wind velocity vector, the temperature, the specific humidity, and the concentration of CO_2. The instrument was mounted at a height of 23 feet above the field. A nested map of the study area is presented on Figure 3-7.

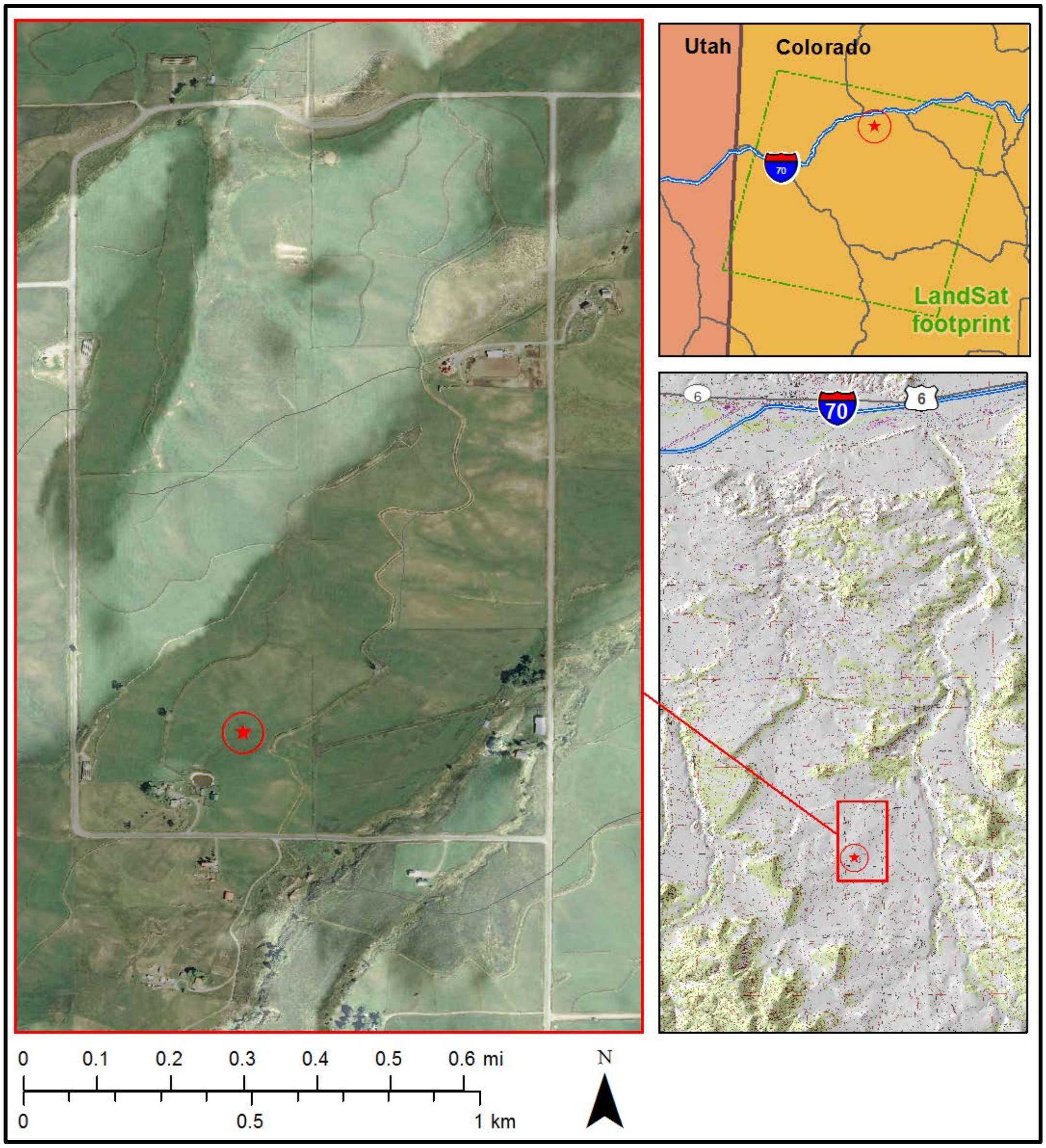


Figure 3-7 Map of the site and surrounding area

Tower setup followed the guidelines discussed in Section 3.5 of this report, and data analysis followed the procedure outlined in Section 3.6. ET was computed on 30-minute intervals for the entire operational period. Some data loss did occur, most notably, an electronic storage failure that spanned a time interval of approximately two weeks. Heavy rainfall and some snowfall also accounted for data loss, and 16 percent of the total data were removed because they fell within the zone of the tower shadow. No footprints inside the tower shadow were included in the comparison with remote sensing techniques per guidance from Campbell Scientific (2013). Figure 3-8 shows the land surface classifications around the EC tower.

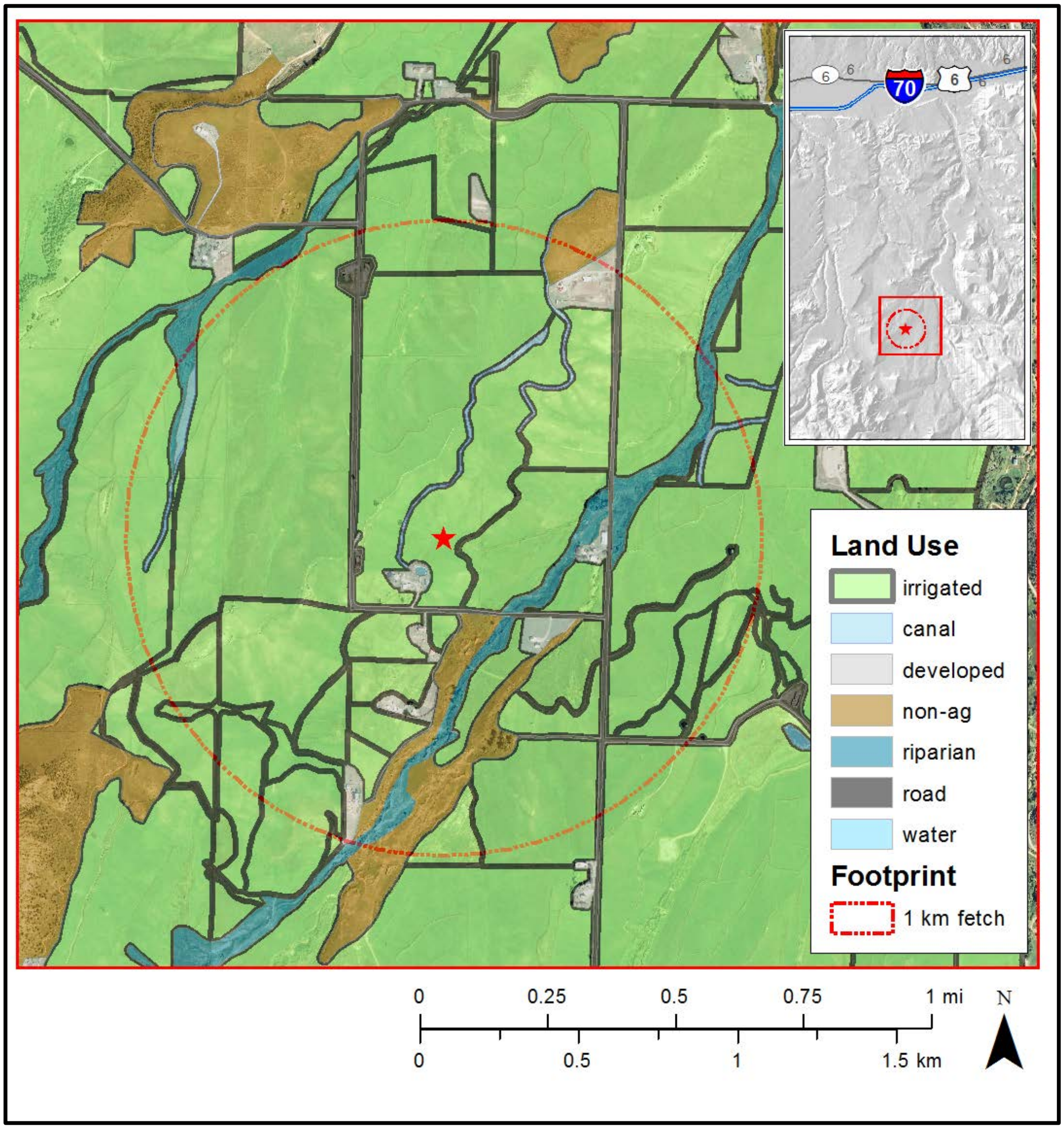


Figure 3-8 Land surface classifications near the EC tower location

The full-time series of the daily ET is provided on Figure 3-9. Here the evaporation peaks at 0.27 inches per day (7 millimeters [mm] per day) at the height of the growing season. The one day of negative ET is associated with heavy rainfall events. The data gap mentioned earlier is clearly visible in this time series. Harvest occurred around day 209.

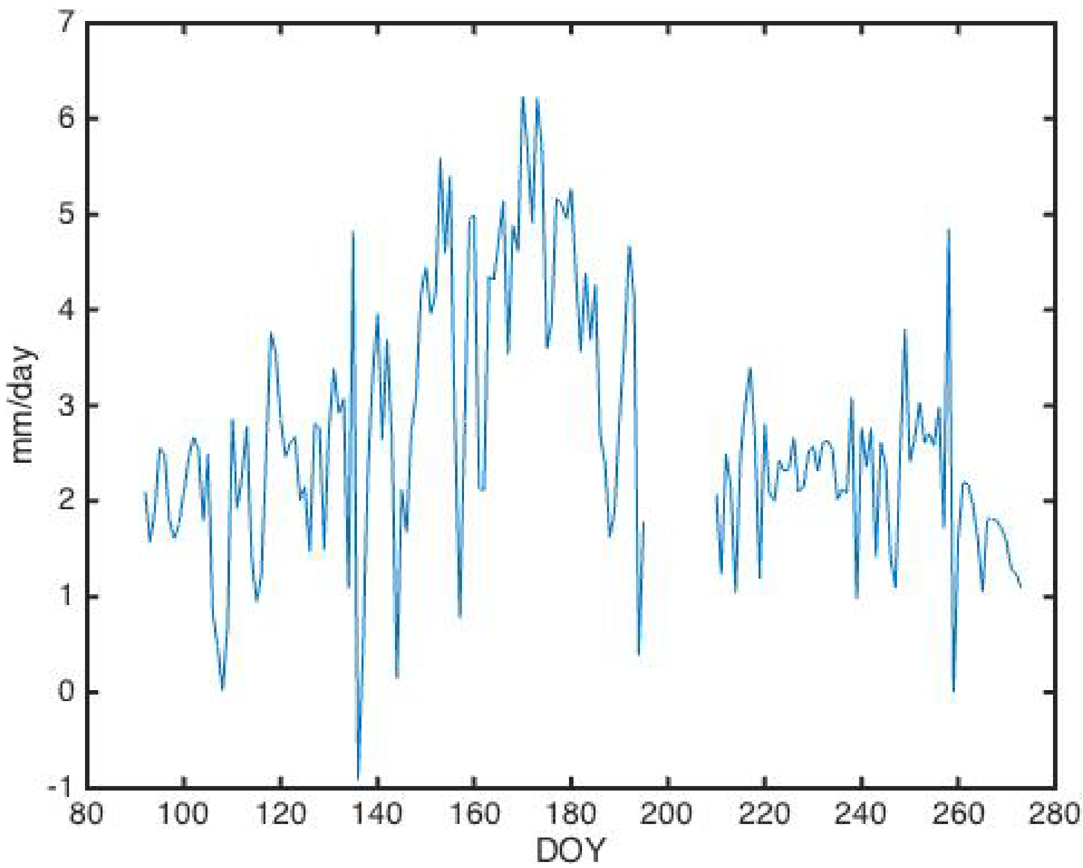


Figure 3-9 Time series of daily ET

Figure 3-10 shows cumulative ET from the irrigated pasture over the entire growing season. The data gap is also visible in this figure. The total ET measured from the field over the course of the season was 450 mm. Precipitation would also need to be measured concurrently to determine the net consumptive water use.

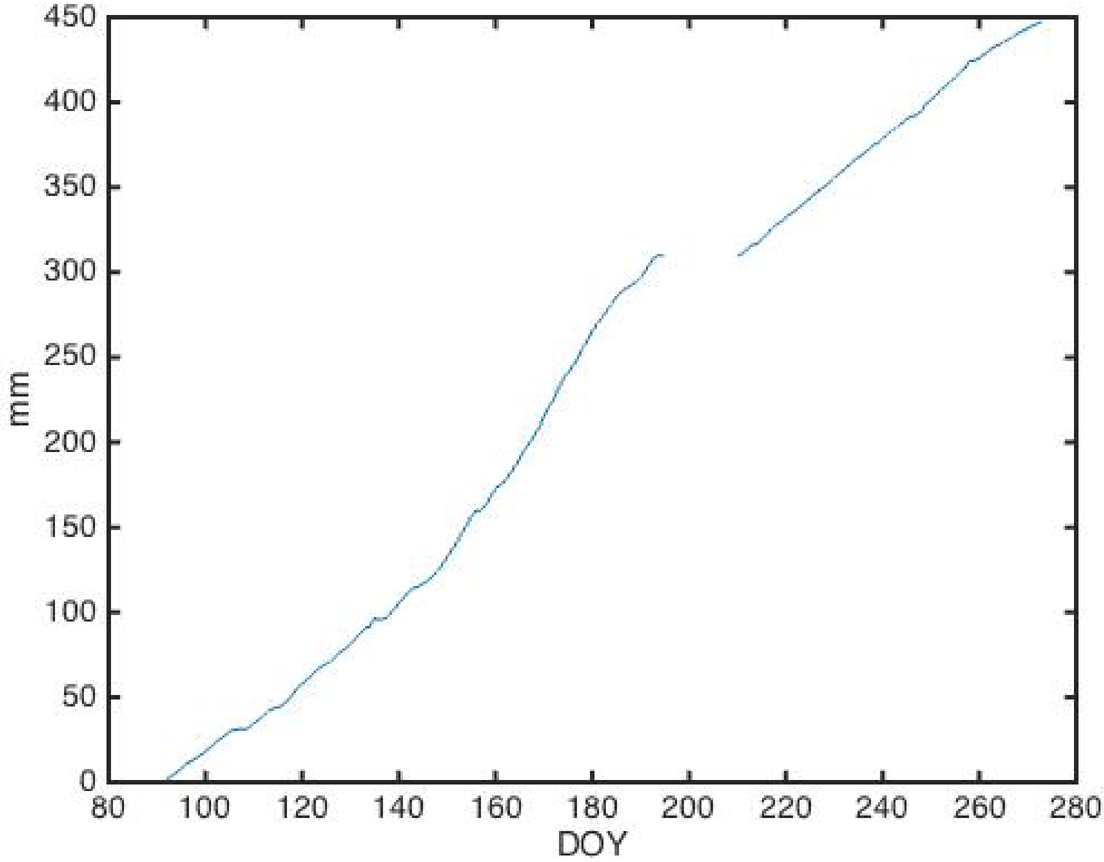


Figure 3-10 Cumulative ET from the irrigated pasture over the entire growing season

3.10 BROADER IMPLEMENTATION

Figure 3-11 presents the study region (blue outline) with the current and planned Extended Climate Stations (green circles) and outlines of the Landsat scenes (red dashed lines).

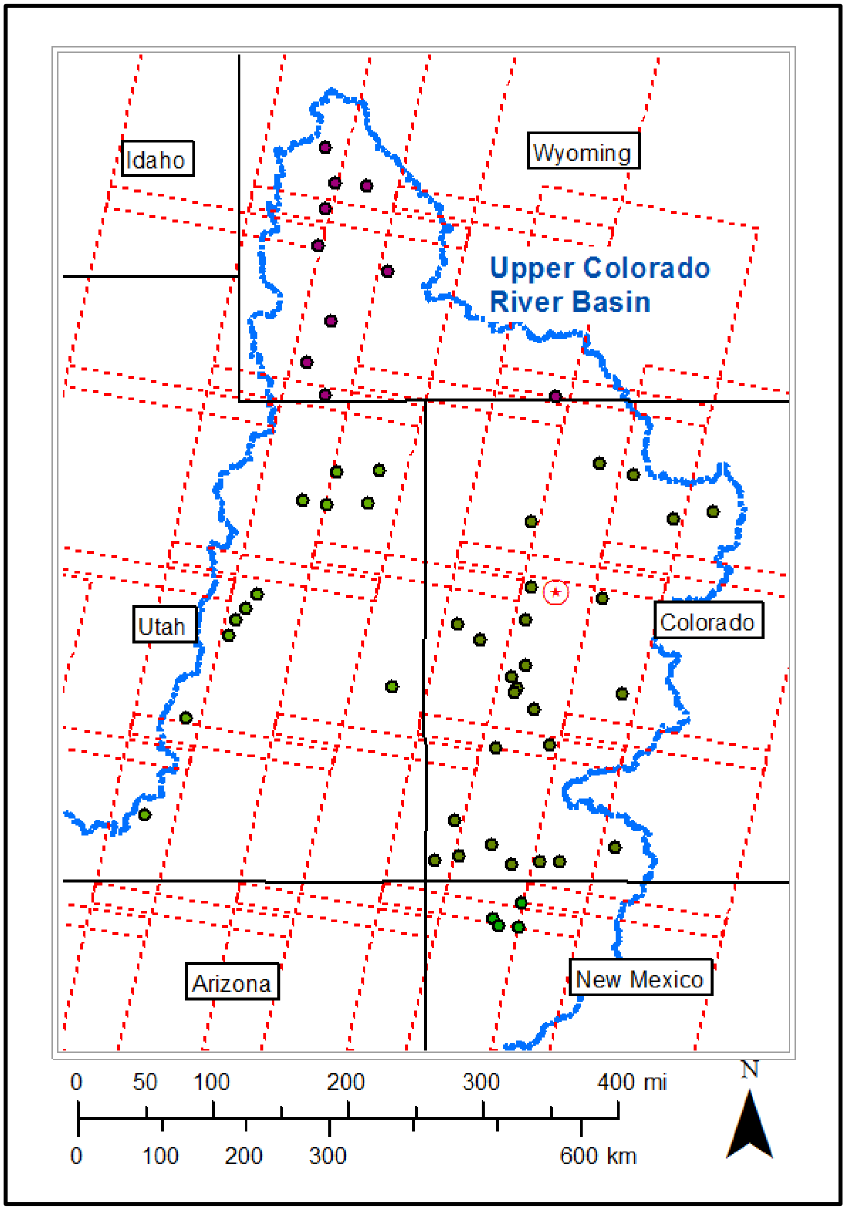


Figure 3-11 Study region showing current and planned extended climate stations and outlines of Landsat scenes

If an EC tower network were to be installed in the UCRB for the purpose of validating both satellite and Penman-Monteith estimates of evaporation, several considerations must be made, as bulleted below.

1. EC tower locations should be near existing or planned Extended Climate Stations or contain the appropriate instrumentation to collect that data to facilitate cross comparison.

2. For Wyoming and New Mexico, where a single scene covers essentially all of the irrigated agriculture, EC tower locations should be near the nadir line of the Landsat 7 satellite overpass. Landsat 7 data far from nadir become sparser due to an issue with the satellite. This is to reduce potential problems with satellite comparisons in the future. For Colorado and Utah, EC towers should be located in the overlap zones with Landsat path 36. The optimal locations would be in the eastern 75 percent of the Grand Valley for Colorado, and in the area between Roosevelt and Vernal in Utah. Given the reality of cloud cover in the UCRB, especially in July and August, locating the stations in overlap zones with path 36 would probably improve the probability of the team of obtaining useable satellite imagery for the EC sites. This suggestion may result in the complete loss of Landsat 7 data for Colorado and Utah.
3. Topographic conditions should be suitable for EC measurements. Places of high relief or dramatic changes in topography are excluded. The 1/3 arc second DEM from the National Elevation Dataset was used to determine local topographic features.
4. EC towers should be located in an irrigated area, but not within an area with overhead moving irrigation systems. Pivots are easily detected from the satellite images, and are excluded. A judgment was also made upon the extent of the irrigated area, and isolated irrigated areas should be excluded.
5. Preference should be given to locations that occur within the overlap of multiple Landsat scenes. In conjunction with bullet 2 above, this restricts overlap within a single path (see Figure 3-12 for the example of Henry’s Fork). In this way, one tower can validate more than one scene.
6. At least two sites should be located in areas where water stress is expected.
7. Preference should be given for logistical ease of access.

The above criteria were used to determine a first- and second-choice candidate for potential EC tower locations across the UCRB. Utah had three potential candidates. *Final decisions on site locations should be made after a boots-on-the-ground visit made by an EC expert.* Other considerations for site selection could include cellular service (for data telemetry) and land owner permissions. Ideally, the sites should be on land that could be purchased or otherwise earmarked for the flux tower.

The total number of EC towers in the network will depend on the available funds and the desired outcomes. If the network’s main function is to validate the satellite estimates of ET, then the ideal scenario would be to have an EC tower in every scene. Using overlapping portions of scenes, this can be accomplished with nine stations if they are carefully placed. If the primary function of the network is to provide a comparison for the climate station Penman-Monteith estimations of ET, then fewer could be used. With the six criteria outlined above, two potential EC tower sites were identified for Colorado, New Mexico, and Wyoming, and three potential EC tower sites were identified for Utah.

State and Rank	Name	Latitude	Longitude
CO #1	Upper Uncompahgre	38.17 N	107.71 W
CO #2	Hayden	40.50 N	107.18 W
NM #1	Farmington	36.68 N	108.32 W
NM #2	Navajo Block 9	36.61 N	108.05 W
UT #1	Pelican Lake	40.17 N	109.67 W
UT #2	Huntington	39.31 N	110.97 W
UT #2	Neola Area	40.42 N	110.00 W
WY #1	Henry’s Fork	41.05 N	110.12 W
WY #2	Budd Ranch	42.53 N	110.12 W

3.10.1 Discussion on Stationary or Moving Towers

To justify the effort and expense of moving a flux tower to a new location (which includes an estimated 20 person-days of labor), the resulting decision power and information must increase. There is not sufficient justification to measure in a new place as the satellite and Penman-Monteith estimations can be validated at any viable location. New data products must emerge as a result of the work. There are a few imaginable approaches which could justify the effort.

1. Creating a site-specific calibration equation that links the outputs of an Extended Climate Station to the EC measurement that leads to permanent improvements in the local Penman-Monteith estimations. The most promising path emerging in the literature now involves an adaptive neural network approach; however, that is still in its infancy, and is untested.
2. Iterative improvement of the network. If the satellite measurements could identify those places within scenes where the uncertainty is highest, the EC tower could be moved to those locations to provide the best potential adjustments. In this scenario, the movement of EC towers would be temporary, and restricted to the first few years of the network’s operation.

Figure 3-12 shows potential EC tower site locations. The locations shown are approximate and could be moved within a 0.6 miles radius; however, each site still needs background research to determine exact locations.

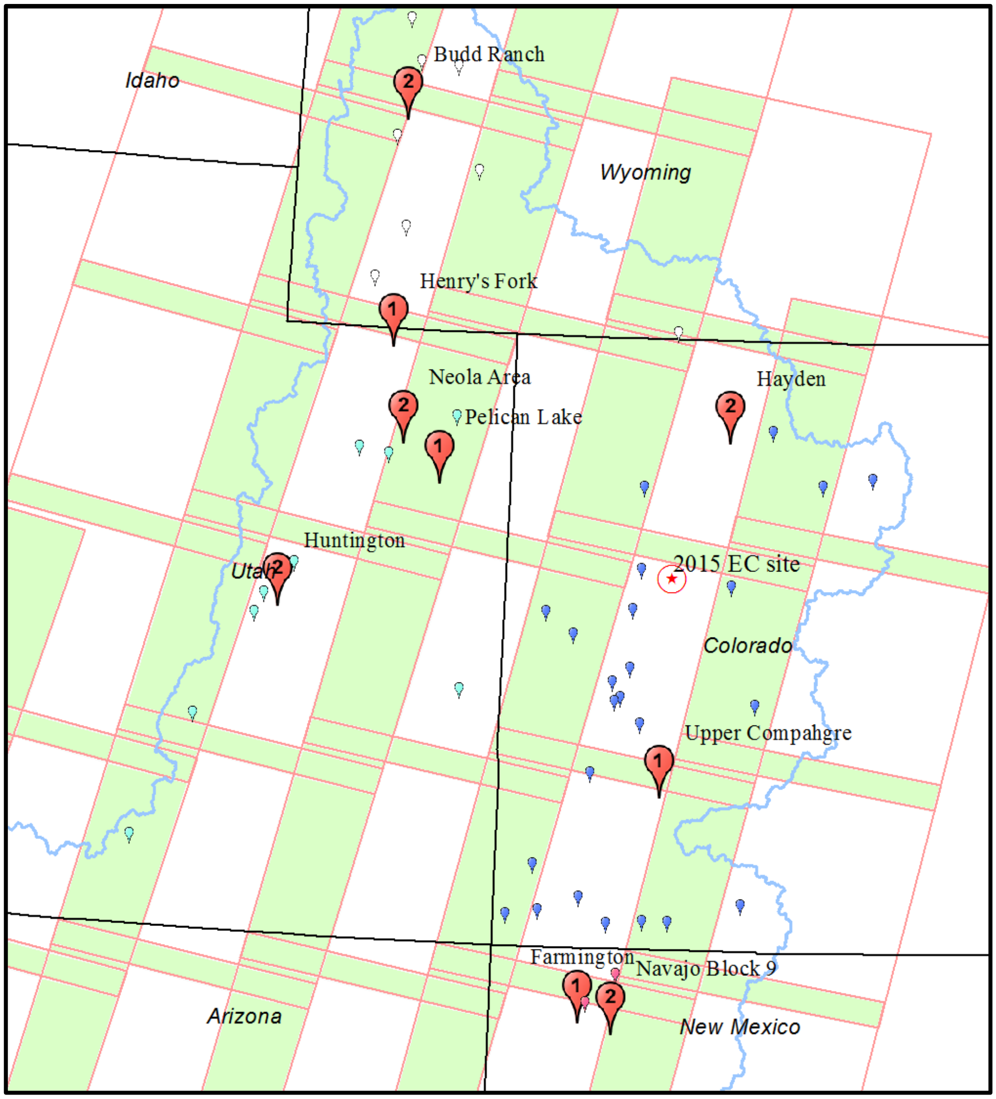


Figure 3-12 Potential EC tower site locations

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4.1 REMOTE SENSING METHODS

The objectives of the remote sensing aspects of this Project were focused on evaluation of the operational applications of various remote sensing methods to estimation of crop ET over agricultural fields of the UCRB. The methods analyzed included the reconstructed METRIC method and the SSEBop method in Colorado, New Mexico, Utah, and Wyoming. Additional space-based SSEBop estimates of ET were made by David Eckhardt (Reclamation – Denver) in Colorado (see Appendix F). These alternative approaches investigated the influence of: 1) the number of scenes analyzed, 2) *c*-factor parameterization, and 3) air temperature dataset (Appendix F). Satellite methods were compared to estimates of reference ET in each state, respectively. A detailed comparison between the satellite methods and a direct measurement of actual ET, measured with an EC tower, were performed in Colorado. The comparison between the EC tower and the satellite estimation methods was made for the subset of satellite image 'pixels' that corresponded directly to the measurement footprint of the EC tower. Inter-comparisons were performed only when data from all sources were available.

4.1.1 R-METRIC

R-METRIC is a reconstructed version of the METRIC method (Allen *et al*. 2002; 2007). METRIC is based on the energy balance at the surface of the earth:

$$R_n = G + LE + H \tag{1}$$

where R_n is the net radiation flux, G is the ground heat flux, LE (latent energy) is the λE flux, and H is the sensible heat flux. METRIC estimates ET at the time of the satellite overpass as the residual of the surface energy balance:

$$LE = R_n - G - H \tag{2}$$

METRIC estimates each component of the surface energy balance individually. R_n is calculated using the surface radiation balance equation. The surface temperature is a major driver and is obtained from the satellite's thermal band. G is calculated using vegetation indices, net radiation, surface temperature, and albedo. H is calculated using wind speed, surface roughness based on land use classifications, and the near-surface temperature gradient (dT).

The temperature gradient is defined by two extreme conditions. In the dry condition, H dominates the turbulent fluxes; H is assumed minimal in the wet condition. These conditions are defined by user-selected pixels, where the dry condition is taken from a bare agricultural field and the wet condition is taken from a well-watered agricultural field; both conditions must also meet certain vegetation parameters. These pixel choices, in conjunction with hourly values of reference ET, allow for the computation of dT, and therefore H, over a full scene; LE can then be calculated according to Equation 2.

The reference ET fraction (*ETrF*) is calculated as the ratio of hourly ET estimated by the remote sensing method to hourly reference ET. *ETrF* values are assumed constant over daytime hours, so daily ET estimates are generated by multiplying *ETrF* by daily reference ET. For days of satellite overpass, *ETrF* values are interpolated on a pixel-by-pixel basis from one image acquisition date to the next. Daily ET estimates are then calculated by multiplying the *ETrF* estimates by daily reference ET. Seasonal ET is estimated by summing daily values.

The R-METRIC algorithms were constructed based on the METRIC applications manual (Allen *et al*. 2010) and other publications describing the METRIC data processing algorithms. There has been no side-by-side comparison of METRIC and R-METRIC on the same Landsat scene using the same hot and cold pixel selection (METRIC is a proprietary data analysis package and a service must be contracted for data analysis). In previous work as part of the National Aeronautics and Space Administration (NASA) AirMOSS project (http://airmoss.jpl.nasa.gov/), R-METRIC gave very similar results to EC tower measured ET (the towers run by University of California, Berkeley) at one site (Viara Ranch), and notably high ET results over the growing season at another site located only a few kilometers away (Tonzi Ranch), and in the same Landsat scene (Ring *et al*. 2014). These results were from a similar version of R-METRIC as that used on this Project, although the version for this Project included the implementation of the mountain model (Allen *et al*. 2010). The hot and cold pixel selection is the key, and for both of these sites, the same person made the hot and cold pixel selection for the season and both sites were in the same scene (i.e., the same hot and cold pixels were used to evaluate the ET from the two tower sites). The criteria used were always those specified by the METRIC manual, but the results are very susceptible to change based on which hot and cold pixels are selected. Different experienced practitioners making hot and cold pixel selections using METRIC resulted in significantly different ET estimates in trials in central Iowa (Long and Singh 2013).

4.1.2 SSEBop (USGS)

SSEB is an acronym for Simplified Surface Energy Balance (Senay *et al*. 2007). SSEBop (USGS) is the operational form of the model (Senay *et al*. 2013), which is executed by the USGS. Unlike METRIC, SSEBop does not solve for the terms of the energy balance separately, but instead assumes a linear relationship between ET and surface temperature. Early versions of SSEB required the manual selection of the hot pixel temperature (where ET is assumed to be near zero) and the cold pixel temperature (where ET is assumed to be near the reference value) - similar to METRIC. SSEBop has been simplified by introducing the use of bias-corrected gridded daily maximum air temperature data to estimate cold pixel temperatures (T_{cold}), and a pre-calculated estimate of the temperature difference between hot and cold pixels (dT [near-surface temperature gradient]) that is added to T_{cold} to estimate the hot pixel temperatures (T_{hot}).

The cold reference value is found as a fraction of near-surface daily maximum air temperature (T_{max}) by the equation:

$$T_{cold} = c\ (T_{max}) \tag{3}$$

where c is a correction factor (called c-factor). The c-factor is typically found statistically as a seasonal average ratio of the surface temperature of vigorous, full canopy vegetation to T_{max}. The USGS standard procedure requires scene-specific c-factors in the UCRB using Landsat imagery. The USGS first bias-corrects the T_{max} data using a multiplicative coefficient so that it matches the recorded T_{max} values measured at the designated Extended Climate Station for each Landsat Path/Row. USGS then uses a statistical method to define the c-factor. An image of *LST* (land surface temperature)/T_{max} is generated, then masked such that only pixels with a Normalized Difference Vegetation Index (NDVI) greater than 0.7 remain. The c-factor is defined as the mean LST/T_{max} value from the masked image, minus two standard deviations.

The temperature gradient, *dT*, is calculated for a given date and place as a function of theoretical clear-sky net radiation and a constant aerodynamic resistance, and constants. The hot reference value is then found by adding *dT* to the cold reference value.

Reference ET fractions can then be calculated using remotely sensed temperature data as:

$$ETrF = (T_{hot} – LST) / dT \quad (4)$$

Actual ET is found by multiplying reference ET by *ETrF*. Thus, the required inputs for SSEBop are thermal data from Landsat 7/8, reference ET, and gridded maximum air temperature.

In addition to the SSEBop run by the USGS, Reclamation performed a sensitivity analysis (Appendix F).

4.1.3 Note on R-ReSET and ALEXI-DisALEXI

Originally, this Project was intended to test two other remote sensing methods to compute ET from a combination of Landsat data along with input data from other databases and/or models. One of these methods was R-ReSET which was to be a reconstructed model of the ReSET (Remote Sensing of Evapotranspiration) method developed by Elhaddad and Garcia (2008) and further developed and applied by David Eckhardt of Reclamation. ReSET requires additional temperature databases and R-ReSET would have required recoding ReSET to MATLAB (which was the coding platform used by HEI. This work was started by Dr. Richard Cuenca; Dr. Cuenca became seriously ill at that time and was hospitalized, thus precluding further development of these other remote sensing methods.

ALEXI-DisALEXI is a model supported by the U.S. Department of Agriculture Hydrology and Remote Sensing Laboratory (HRSL) and is currently coupled with the FUSION model for interpolation in time and space. Cooperation between HEI and HRSL resulted in the thesis of Theresa Ring who interned for a number of months at HRSL and who previously worked on development of R-METRIC for this Project. HRSL personnel indicated they would cooperate with this Project Team as an example of support for ALEXI/DisALEXI to the extent possible, and they were sent all remote sensing and meteorological data sets that had been sent to the other Project Team members. However, while the other Project Team members were doing data processing, ALEXI/DisALEXI was undergoing continued development, and particularly, the FUSION interpolation scheme. This work was not completed until the end of the growing season and HRSL was not able to process the data in a timely manner for consideration in this report.

4.2 OPERATIONAL REQUIREMENTS

The time to run each model is highly dependent on the computer central processing unit and random access memory (RAM). The recommended equipment is a high-end desktop computer with maximum RAM and hard disk space of multiple terabytes (approximately $3,000).

All methods require the acquisition and processing of meteorological data to calculate reference ET. Each meteorological network stores data in a different format. Excel templates were developed at the beginning of the year and new meteorological data were added to the existing Excel templates. A MATLAB script was used to compute Penman-Monteith reference ET, but this calculation could be scripted in any language. These data were distributed to all users and used in the calculation of ET_a (actual evapotranspiration) for all remote sensing methods.

The comparison with the EC tower, aggregation of each method, and comparison between methods were scripted in MATLAB. Sample costs for MATLAB are indicated in Table 4-1.

Table 4-1. Software costs – MATLAB

Product	Price
MATLAB - Prerequisite Platform	$2,150
Image Processing Toolbox	$1,000
Mapping Toolbox	$1,000
Statistics and Machine Learning Toolbox	$1,000
Total	**$5,150**

4.2.1 R-METRIC

R-METRIC is a reconstructed version of the METRIC model. R-METRIC, which was originally modeled using ERDAS Imagine, was scripted using MATLAB for this Project. Cloud masking, gap-filling, and interpolation are MATLAB-based and automated. The time for each step is shown in Table 4-2. Hot and cold boundary pixel selection was conducted by visual inspection in ArcGIS.

Table 4-2. Remote sensing data analysis requirements for the UCRB using R-METRIC and assuming 20 satellite overpasses per season and 18 scenes per overpass to cover the UCRB

Task	Time Required	Task Period	Hours/ Season
Met Data Acquisition	30-min	Every Scene	180
Scene Preview	10-min	Every Scene	60
Hot/Cold Pixel Selection	30-min	Every Scene	180
Computations	15-min	Every Scene	90
Gap Filling	5-hours	Seasonally	20
Interpolation	5-hours	Seasonally	20

Analyzing the entire basin using R-METRIC is a 0.35 full-time equivalent job. Approximately one week of training is required for the competent individual (Bachelor of Science graduate with 3 years of remote sensing/geographic information system [GIS] data analysis experience or a Master's graduate with 1 year of remote sensing/GIS data analysis experience). In the best-case scenario, full automation could save 180 hours per year. However, hot and cold pixel selection cannot be fully automated.

4.2.2 SSEBop (USGS)

SSEBop (USGS) is scripted in Python. The scripts require installation of ArcGIS 10.x in order to use the functions from the ArcPy Python package. Cloud masking, gap-filling, and interpolation are all Python-based and automated.

4.3 OPERATIONAL DIFFICULTIES

4.3.1 Cloud Cover

Satellites are only able to detect surface temperatures if there are clear skies at the time of image acquisition (see Table 4-3). If the sky is not clear, the thermal band returns the temperature at the top of the cloud. Landsat provides a CF Mask to help users identify clouds. Although the CF Mask is reliable for identifying clouds with distinct boundaries, it does not always identify thin clouds that increase Landsat-based ET estimates.

Table 4-3. Number of scenes used for each path/row combination for areas of interest for each state in the UCRB

State	Path/Row	Numer of Scenes
Colorado	35/33	17
New Mexico	35/35	19
Utah	37/32	19
Wyoming	37/30	15

Even if light clouds are effectively masked, their influence on surface temperature can reduce the accuracy of ET estimates produced by both METRIC and SSEBop. Areas that have been in direct sunlight for longer periods of time prior to image acquisition will exhibit larger temperature differences between hot and cold pixels than areas that have experienced greater cloud cover prior to image acquisition. Accuracy of local ET estimates will depend in large part on how closely the portion of the image used for remote sensing model calibration (i.e., hot and cold pixel selection) matches the weather conditions at any given location during the hours leading up to image acquisition.

More significantly, the *dT* values calculated by SSEBop assume clear-sky conditions prior to image acquisition. Variable cloudiness reduces the solar radiation available to warm the surface during the morning hours prior to image acquisition, producing *dT* values significantly less than those predicted by the clear-sky model. This situation tends to produce overestimates of ET by SSEBop, as more of the image *LST* data are crowded near the cooler end of the prescribed *dT* range.

Regardless, all remote sensing methods utilized the CF Mask to eliminate clouds from the image processing. This leads to missing data, which must be interpolated. *ETrF* from previous and subsequent cloud-free scenes were used to interpolate *ETrF* for each cloud-masked pixel (Allen *et al*. 2002).

End-of-season data for Path 35 was contaminated by cloud cover, so an image from after the September 30, 2015 end date was used for late-season interpolation.

4.3.2 Missing Meteorological Data and QC of Meteorological Data

All methods require meteorological data on an hourly timestep in order to compute reference ET for alfalfa using the Penman-Monteith method. The necessary variables are incoming solar radiation, air temperature, relative humidity (RH), wind speed, and precipitation.

The primary weather station and source for each state are shown in Table 4-4.

Table 4-4. Primary (and secondary, in the case of New Mexico) weather stations and data sources for each state in the UCRB

State	Meteorological Station	Data Source
Colorado	Olathe 2	CoAgMet
New Mexico	Farmington / Block 1	NMCC/NAPI
Utah	Pleasant Valley	AgriMet
Wyoming	Boulder	HPRCC

Using different weather networks requires careful use because standards for data QA/QC are not uniform between networks. AgriMet and HPRCC perform QA/QC. CoAgMet does not, but the Project Team was able to have QA/QC performed by Jama Hamel at the Reclamation. NMCC and NAPI do not perform QA/AC.

The problematic nature of the lack of QA/QC became apparent when the intended station for New Mexico, Farmington, was non-operational from day of year (DOY) 121 (01 May) to DOY 180 (29 June) 2015. The Project Team was able to obtain access to a station located approximately 20 kilometers (km) away that is operated by NAPI. A preliminary comparison of the data from the two stations clearly indicated why QA/QC of meteorological data is necessary. Temperature compared well between the two sites. Block 1 sensors only recorded maximum and minimum RH, so these were averaged for use in Penman-Monteith. A comparison between these RH measurements showed a clear problem with the Farmington RH sensor before DOY 121. Comparing wind speed and wind direction showed many data points where both were 0 at Farmington, indicating missing data, so these were set to not a number (NaN). The Block 1 wind speed height is the non-standard height of 3.327 meters (m); it was adjusted to be comparable to the standard 2-m height according to Allen *et al*. (1998). Incoming solar radiation showed a surprising amount of scatter for two sites located only 20 km apart. This analysis also showed a large number of days where solar radiation dropped to 0 at Farmington in the middle of the day; such erroneous points were removed.

This QA/QC was informal and was only performed because the Project Team was switching sites in the middle of the season; without that, it is possible that the problems at Farmington would not have been discovered. It is clear that networks require QA/QC to be reliable for use in remote sensing applications.

4.3.3 Interpolating Between Days of Satellite Overpass

By utilizing both Landsat 7 and 8 data, a regular schedule would show satellite overpass every 8 days. Interpolating between days of satellite overpass is required to obtain seasonal ET estimates. All remote sensing methods used a temporal linear interpolation. The METRIC

Applications Manual (Allen *et al.* 2010) guidelines recommend a cubic spline interpolation; however, a linear interpolation was used to facilitate comparison with the other methods. Daily actual ET is calculated by linearly interpolating *ETrF* between days with valid satellite measurements, then multiplying these interpolated values by daily reference ET.

4.3.4 SLC Failure for Landsat 7 Data

Landsat 7's Scan Line Corrector (SLC) failed in 2003. The SLC is used to provide contiguous coverage within a scan; without it, Landsat 7 produces significant data gaps. Data loss is estimated at approximately 20 percent and is concentrated at the edges of the scenes. More overlap exists near the center of scenes (USGS 2003). All methods addressed these data gaps in the same way as cloud-covered pixels.

4.3.5 Effects of Field Cutting with Immediate Decrease in ET (as shown by the EC Tower) Between Days of Satellite Overpass

When a field is cut, an EC tower will immediately sense the change and measure a decrease in ET. However, assuming the cut occurs toward the middle of satellite overpass, the remote sensing estimates will not reflect the change in land surface conditions until another satellite overpass occurs. Thus, *ETrF* estimates made by remote sensing methods immediately after field cutting should overestimate ET compared to what the EC tower measures. However, if the satellite image is acquired immediately after the field is cut, the *ETrF* values will be small, and these small values will be temporally interpolated to the most recent preceding image acquisition date. In this case, the *ETrF* estimates made by the remote sensing method will tend to underestimate ET compared to that measured by the EC tower. Ultimately, errors in ET estimates by the remote sensing methods are unavoidable and will vary in magnitude and sign depending on the time of satellite overpass relative to the time of cutting. Some adjustments could be made if the exact date of field cutting is known.

On approximately July 28, 2015, the field where the EC tower was located was cut from approximately 0.9 to 0.05 m.

4.3.6 Shapefiles at Edges of Scenes

This Project was intended to assess actual ET on irrigated lands. Wilson Water Group provided shapefiles that defined the irrigated area for each state. However, the Landsat 7 and 8 satellites image a slightly different area at each overpass. Ideally, fields on the edges of the scenes that were only sometimes covered by satellite overpass would not be included in the remote sensing estimates. However, the true boundary is unknown until the end of the season, when all satellite overpasses have been completed. Waiting until the end of the season to determine the area of analysis is impractical.

SSEBop's processing routine at USGS utilizes the WRS-2 Path/Row shapefiles (produced by the USGS) to constrain the statistical parameterization and output extent. To move forward, all remote sensing methods intersected the WRS-2 boundaries with the irrigated acreage shapefiles from Wilson Water Group. This decision allowed for a direct comparison between methods.

4.4 COMPARISON OF ET ESTIMATES WITH COLORADO EC TOWER

4.4.1 Description of EC Tower Footprint Analysis

The EC tower measures ET from a variable contributing area based on atmospheric conditions. In order to directly compare ET measured by the EC tower with ET estimated by the remote sensing methods, a daily footprint of contributing area was determined.

The Schmid (1994) model was used to find a footprint corresponding to each 30 minutes, starting 1.5 hours after sunrise and ending 1.5 hours before sunset. This data timeframe was chosen because atmospheric stability conditions lead to almost infinite footprints around sunrise and sunset, which is intractable for analysis. A 30-minute measurement period was chosen to correspond with the averaging period used for the EC tower analysis.

Input parameters for the Schmid model primarily come from the EC tower. These variables are the observation point height, Obukhov length, standard deviation of lateral wind speed fluctuations, and friction velocity. Surface roughness length is also required. Surface roughness length was estimated by measuring crop height at regular site visits and linearly interpolating between observations. Crop height was translated to roughness length using the procedure from Food and Agriculture Organization of the United Nations, Rome, Italy, *Crop Evapotranspiration*, Irrigation and Drainage Report 56 (Allen *et al*. 1998).

Footprints when the wind direction was in the EC tower shadow were removed. For gaps of approximately 1 hour, ET was estimated by linear interpolation. Approximately 10 footprints from strongly stable conditions outside of the time period mentioned above were also removed.

The Schmid (1994) model produces an oval footprint that is mathematically estimated by two half-ellipses. Each footprint is oriented to the mean wind direction corresponding to that half-hour time period. A weighting matrix for the area surrounding the EC tower was developed for each day. A 30-meter grid georeferenced to the Landsat image pixels was created for each 30-minute interval, with a binary “in the fetch area” or “outside the fetch area” designation for each grid cell. That is, cells in the fetch area were given the value of 1, and cells outside the fetch area were given the value of 0. Pixel values in each of these 30-minute fetch grids were normalized by dividing by the number of cells identified as being within the fetch area. For each day, the 30-minute fetch grids were added together and divided by the number of 30-minute periods used in the daily fetch calculation. By multiplying the weighting matrix by the ET from each Landsat pixel as estimated by the remote sensing teams, a direct comparison between the ET measured by the EC tower with the ET estimated by the remote sensing methods is achieved.

EC tower data from 8 AM on July 13 until 5:30 PM on July 30, 2015, was lost. This time period was excluded from the comparison.

4.4.2 Results for Each Method

Figure 4-1 shows a comparison of EC tower cumulative ET ground-truth data for the 2015 growing season. The vegetative surface for reference ET for this report is alfalfa, which corresponds to the reference ET applied in the remote sensing methods covered in this report. (The alternative reference ET vegetative surface applied in other work is grass and one must be careful in applying crop coefficients which correspond to the reference ET surface.) The alfalfa reference ET surface is 50-centimeters tall, therefore having an aerodynamic roughness similar to many field crops, disease and weed free, and never short of water. The grass field surrounding the EC tower will not physiologically resemble alfalfa and cannot be expected to otherwise have the attributes of the alfalfa reference surface. Olathe 2 was selected as the primary reference ET station for path/row 35/33. In a comparison with six other meteorological stations in Colorado, the reference ET results from this station were biased neither high nor low but represented a median value.

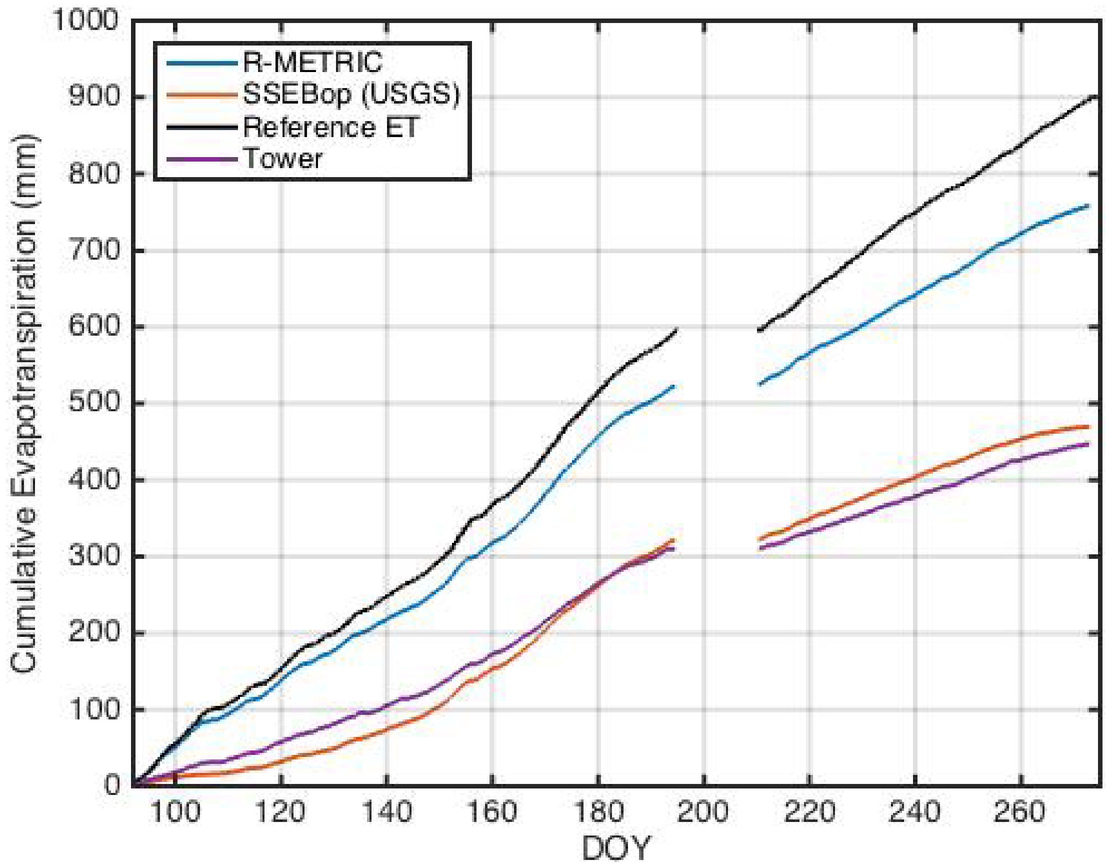

Figure 4-1 Comparison of EC tower cumulative ET ground-truth data for the 2015 growing season with various remote sensing estimating methods; Penman-Monteith ET for a reference alfalfa surface using Olathe 2 weather station data is also plotted as an upper boundary condition, indicating the EC tower site near Rifle, Colorado, was under some water stress during the 2015 growing season

The results of R-METRIC and SSEBop (USGS) remote sensing estimating methods compared with the EC tower measured ET is demonstrated for seasonal daily time-steps in Figures 4-2 and 4-3 while the results of regression equations fit through the data are given in Table 4-6. The results for SSEBop (USGS) plotted in Figure 4-2 indicate considerable scatter about the 1:1 line without a clear bias. Figure 4-3 indicates similar results plotted for R-METRIC. In this case the positive bias is quite clear and produces the positive bias for this method in Figure 4-1.

On Figures 4-2 and 4-3, days of satellite overpass are shown in red. This presentation was done in order to remove the effects of the linear interpolation scheme between days of satellite overpass. The points corresponding to days of satellite overpass show similar trends as the seasonal data with SSEBop (USGS) that shows the least bias, while R-METRIC shows a distinct positive bias.

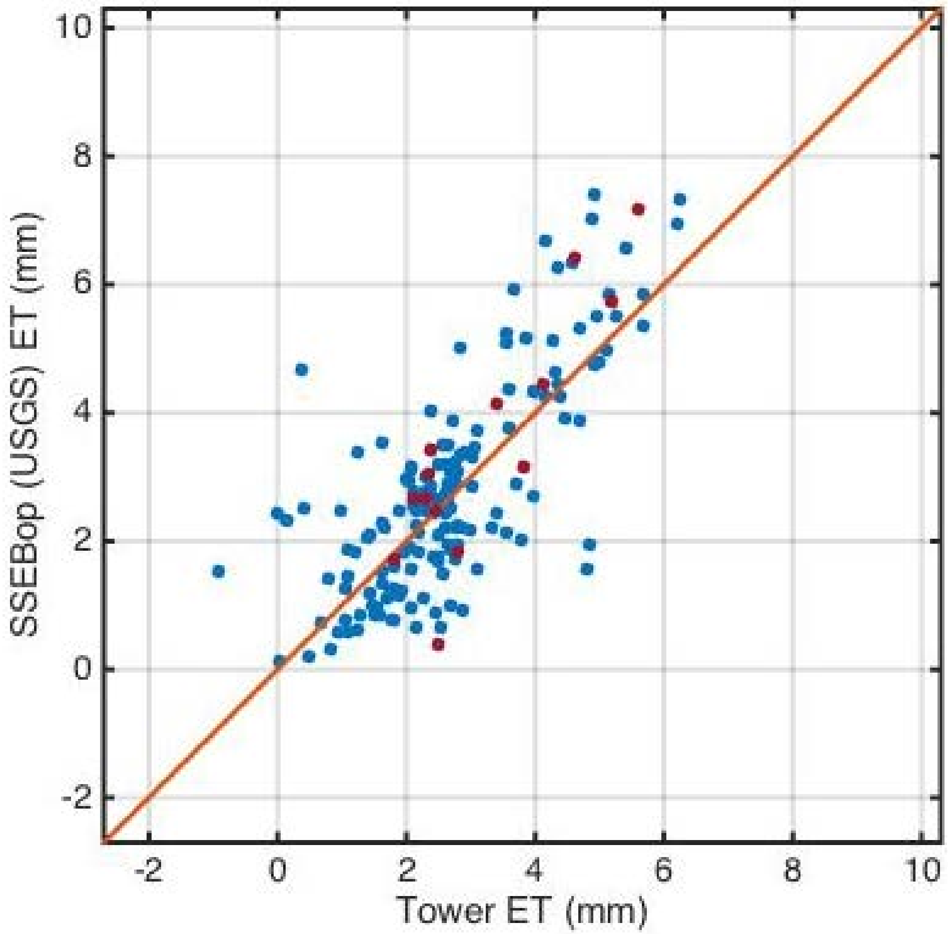

Figure 4-2 Comparison of EC tower daily ET ground-truth data throughout the 2015 growing season with USGS SSEBop remote sensing estimated daily ET (1:1 line indicated in orange)

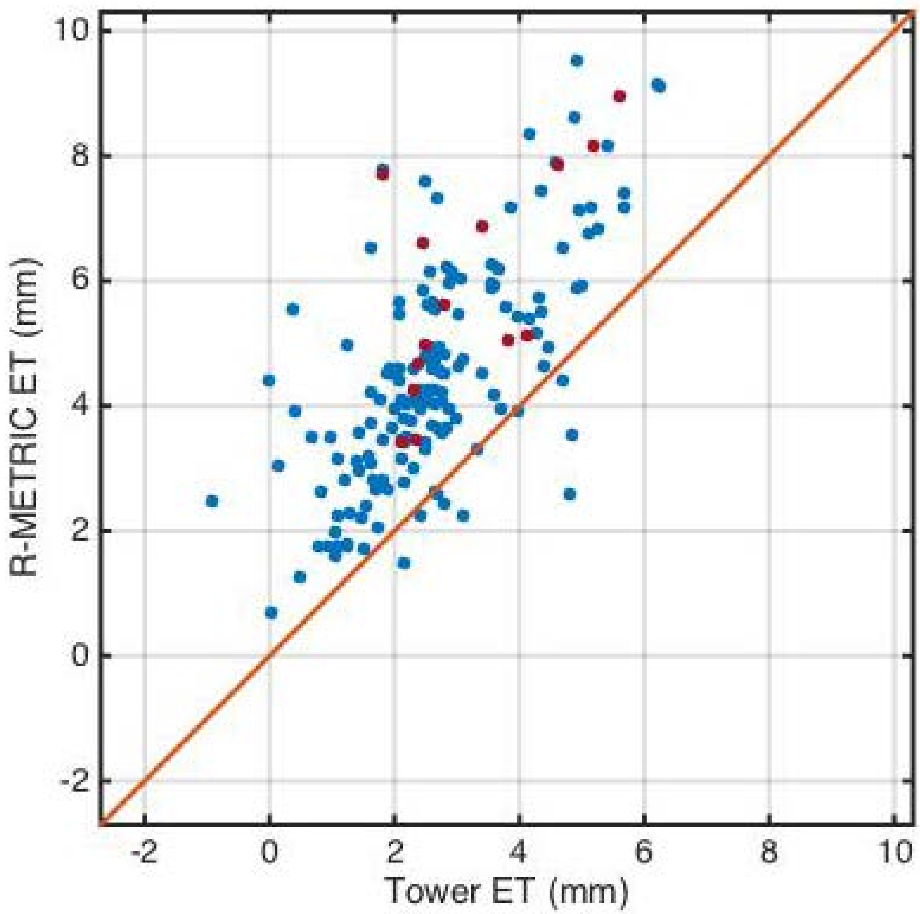

Figure 4-3 Comparison of EC tower daily ET ground-truth data throughout the 2015 growing season with R-METRIC remote sensing estimated daily ET (1:1 line indicated in orange)

The linear least squared error regression models generated from the 182 data points are presented in Table 4-5. Both methods have a positive intercept with the low value of 0.60 for SSEBop and a high value of 2.18 for R-METRIC. The slopes of the equations are similar, with a value of 0.92 for R-METRIC and 0.89 for SSEBop (USGS). Table 4-5 also indicates the coefficient of determination for both methods and the root mean square error (RMSE). Both of the *R*-squared values are relatively similar and low which is evidenced by the scatter of the data around the 1:1 line. The values of the RMSE range from a low of 1.22 for SSEBop (USGS) to a high value of 1.32 for R-METRIC.

Table 4-5. Coefficient of determination and root-mean-squared error for linear regression lines through full season of daily ET for various remote sensing methods

Remote Sensing Method	Linear Regression Equation	No. Data Pairs	*R-squared*	*RMSE (mm/d)*
R-METRIC	$ET_{rs} = 0.92\ (ET_{tower}) + 2.18$	182	0.45	1.32
SSEBop (USGS)	$ET_{rs} = 0.89\ (ET_{tower}) + 0.60$	182	0.47	1.22

Similar linear regression statistics as previously described are provided in Table 4-6. The *R*-squared value is quite low for R-METRIC and much higher for SSEBop (USGS). This is surprising since no interpolation with time is included; these are the most direct comparison of the estimating methods to the EC tower measured ET.

Table 4-6. Coefficient of determination and root-mean-squared error for linear regression lines through daily ET estimated by various remote sensing methods on days of satellite overpass

Remote Sensing Method	Linear Regression Equation	No. Data Pairs	*R-squared*	*RMSE (mm/d)*
R-METRIC	$ET_{rs} = 0.95\ (ET_{tower}) + 2.81$	14	0.43	1.41
SSEBop (USGS	$ET_{rs} = 1.35\ (ET_{tower}) - 0.87$	14	0.76	0.96

4.5 COMPARISON OF CUMULATIVE ET FOR IRRIGATED LANDS BY STATE FOR EACH METHOD

4.5.1 Description of Method to Compute Cumulative ET Volume by State

Interpolating between days of satellite overpass is required to obtain seasonal ET estimates. Each method used a temporal linear interpolation to estimate daily actual ET for only fields within the irrigated shapefiles provided by Wilson Water Group. For each state, ETa was summed and normalized by the total area of the fields in the irrigated shapefiles to produce a cumulative actual ET in millimeters per day (mm/d) for the duration of the growing season.

Remote sensing methods allow for the estimation of seasonal ETa without knowledge of crop type by field. Crop type is required in order to estimate ET using crop coefficients in conjunction with Penman-Monteith reference ET.

4.5.2 Results for Each State

Figure 4-4 shows spatially distributed cumulative seasonal ET for Colorado (clipped to better show the irrigated areas). Note that there are some fields with very low ET. Results in Figure 4-5 show that R-METRIC produces the highest cumulative seasonal ET estimate.

Figure 4-6 shows the timeseries of average daily ET for R-METRIC, SSEBop (USGS), and reference ET. Scenes used for each method are indicated as circles on the plot. It is interesting that the only day where SSEBop and R-METRIC produced close to the same ET estimates was on a day where the EC site was slightly obscured by thin clouds that were not masked by the CF Mask (DOY 201). It has been noted (David Eckhardt, Reclamation - Denver, personal communication) that SSEBop tends to overpredict *dT* on partly cloudy days when the lack of clear-sky conditions prior to image acquisition does not warm up the land surface as much as the SSEBop model expects under the clear-sky assumption. But SSEBop possibly does a better job on clear days after rain events because it is not biased by bare soil pixels that were cooler than expected due to evaporation from the soil surface.

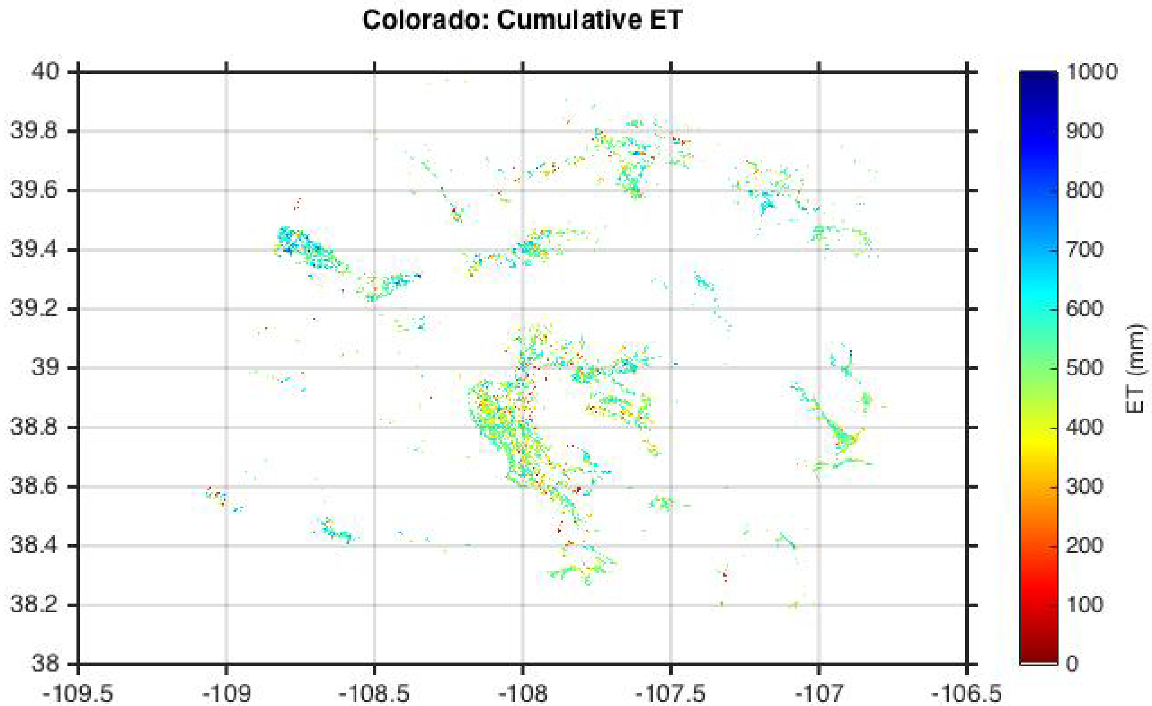

Figure 4-4 Cumulative seasonal ET for the 2015 growing season for the Colorado area of interest estimated using the USGS SSEBop remote sensing method (Gridlines indicate latitude and longitude)

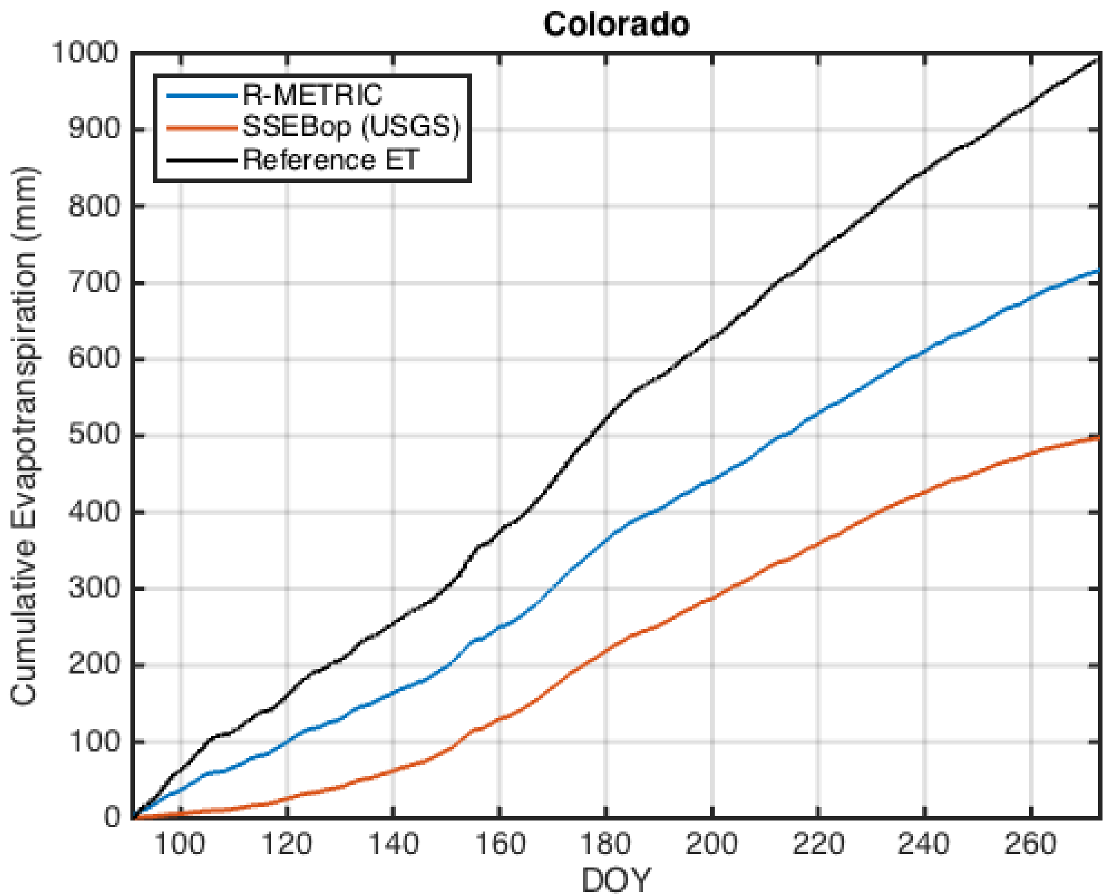

Figure 4-5 Cumulative seasonal ET estimated using R-METRIC and the USGS SSEBop remote sensing methods; Penman-Monteith ET for a reference alfalfa surface using Olathe 2 weather station data is included for comparison

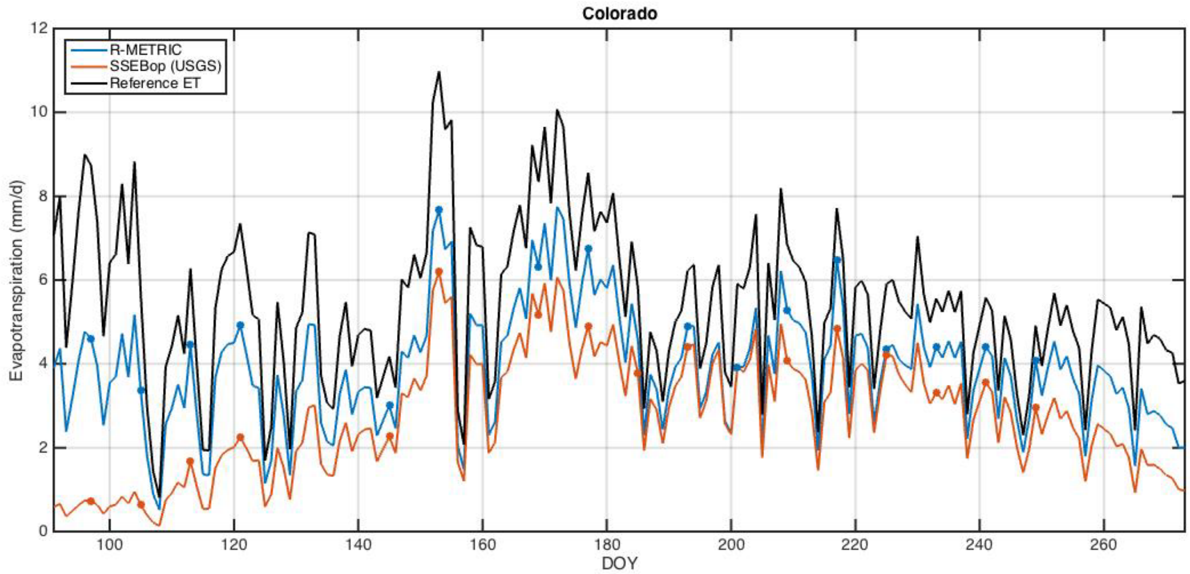

Figure 4-6 Average daily ET throughout the 2015 growing season for all irrigated lands in the Colorado area of interest estimated using the USGS SSEBop and R-METRIC remote sensing methods; Penman-Monteith ET for a reference alfalfa surface is included for comparison

New Mexico's spatially distributed cumulative ET is presented in Figure 4-7. Figure 4-8 demonstrates that again, R-METRIC produces a higher seasonal estimate than SSEBop (USGS). The daily means show that there is a larger gap between reference ET and remote sensing estimates as compared to Colorado (Figure 4-9). Days of satellite overpass for each method are indicated as circles on Figure 4-9.

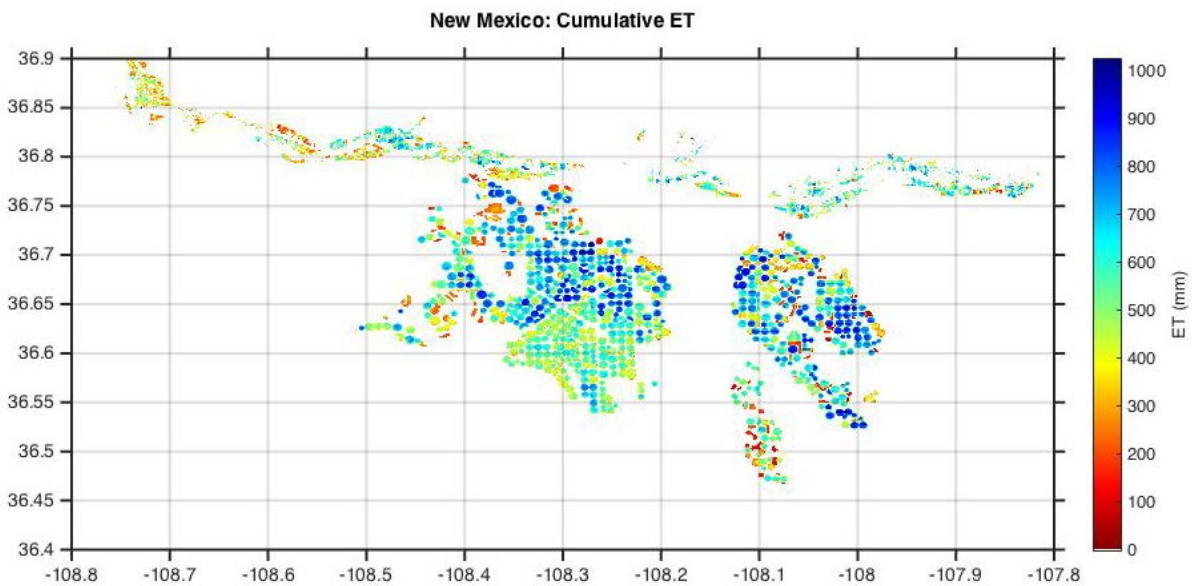

Figure 4-7 Cumulative seasonal ET for the 2015 growing season for the New Mexico area of interest estimated using the USGS SSEBop remote sensing method (gridlines indicate latitude and longitude)

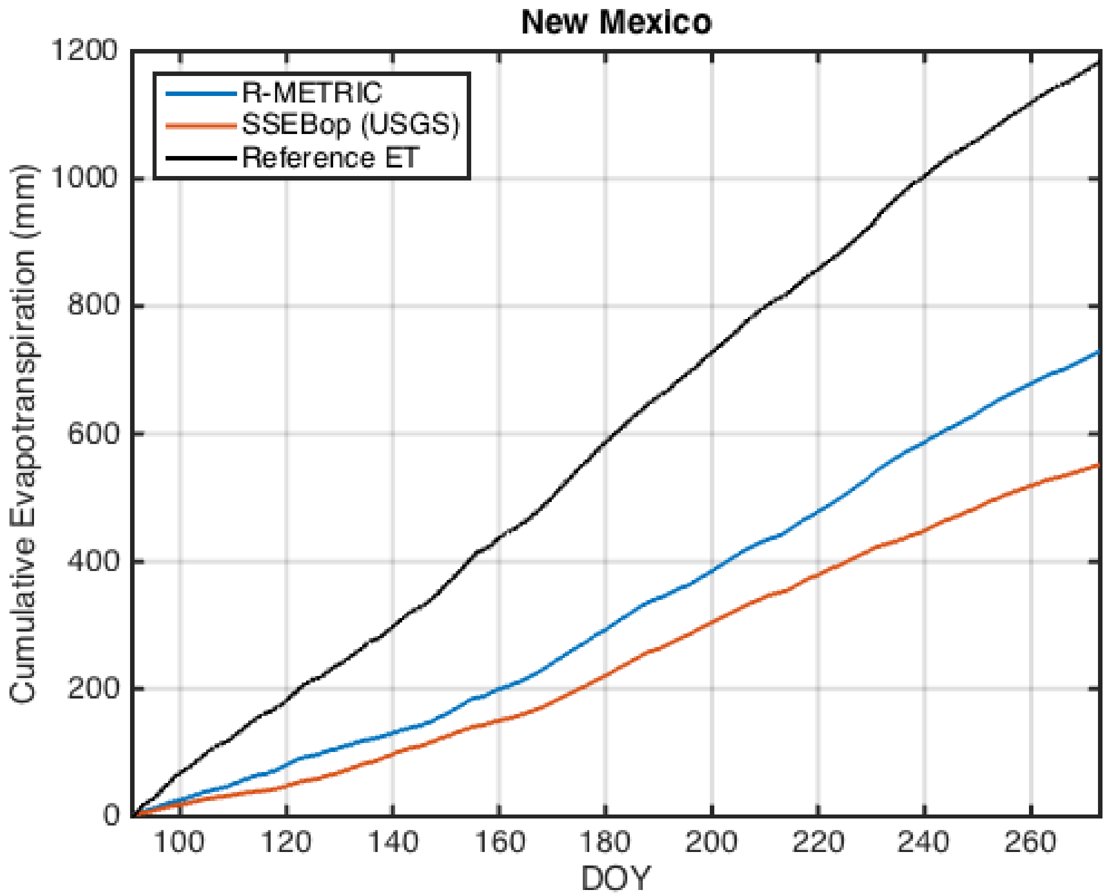

Figure 4-8 Cumulative seasonal ET estimated using R-METRIC and the USGS SSEBop remote sensing methods; Penman-Monteith ET for a reference alfalfa surface using Farmington and Block 1 weather station data is included for comparison

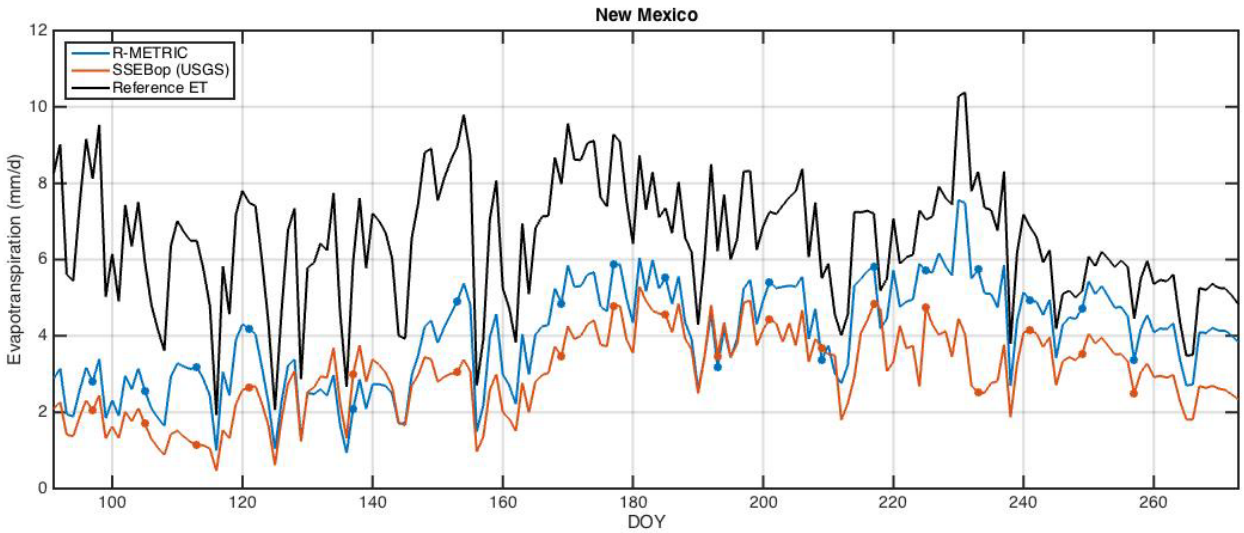

Figure 4-9 Average daily ET throughout the 2015 growing season for all irrigated lands in the New Mexico area of interest estimated using the USGS SSEBop and R-METRIC remote sensing methods; Penman-Monteith ET for a reference alfalfa surface is included for comparison

Figure 4-10 shows the spatially-distributed cumulative ET for the Utah area of interest. The cumulative ET shows that R-METRIC tracked reference ET more closely. SSEBop (USGS) again produces the lowest estimate (Figure 4-11). Looking at the daily means (Figure 4-12) shows that the early-season estimates produced by SSEBop (USGS) are much lower than reference ET and the estimates produced by R-METRIC. Again, days of satellite overpass used for each method are indicated as circles.

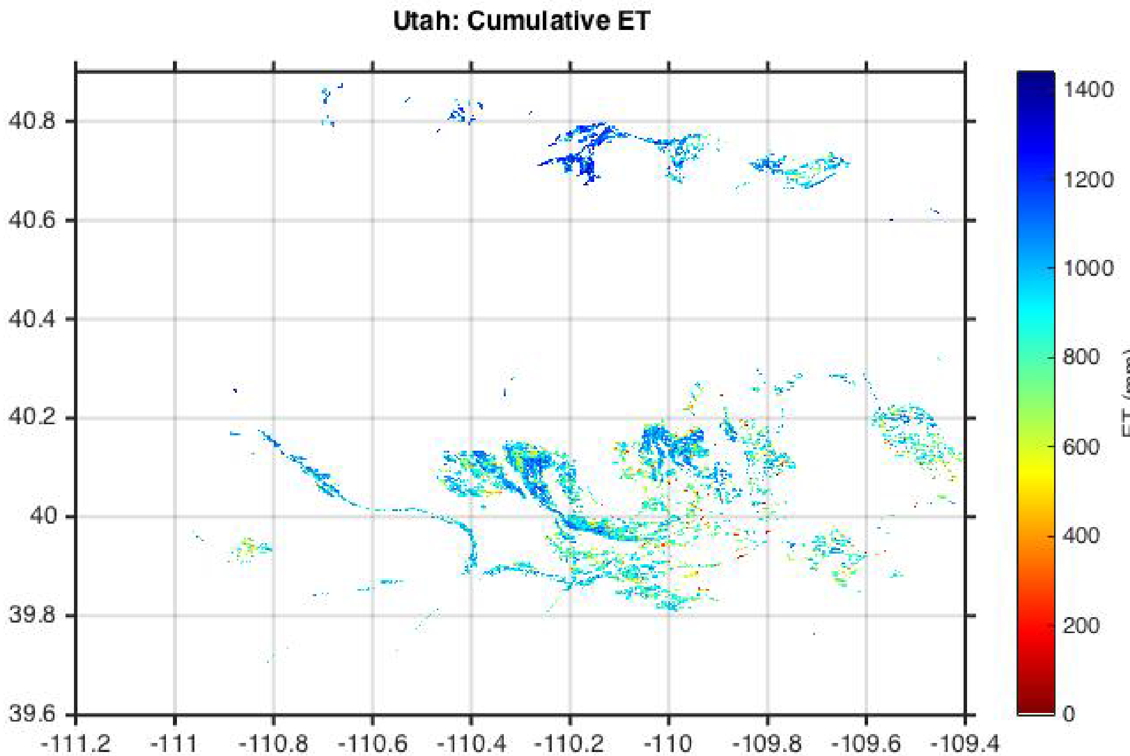

Figure 4-10 Cumulative seasonal ET for the 2015 growing season for the Utah area of interest estimated using the R-METRIC remote sensing method (gridlines indicate latitude and longitude)

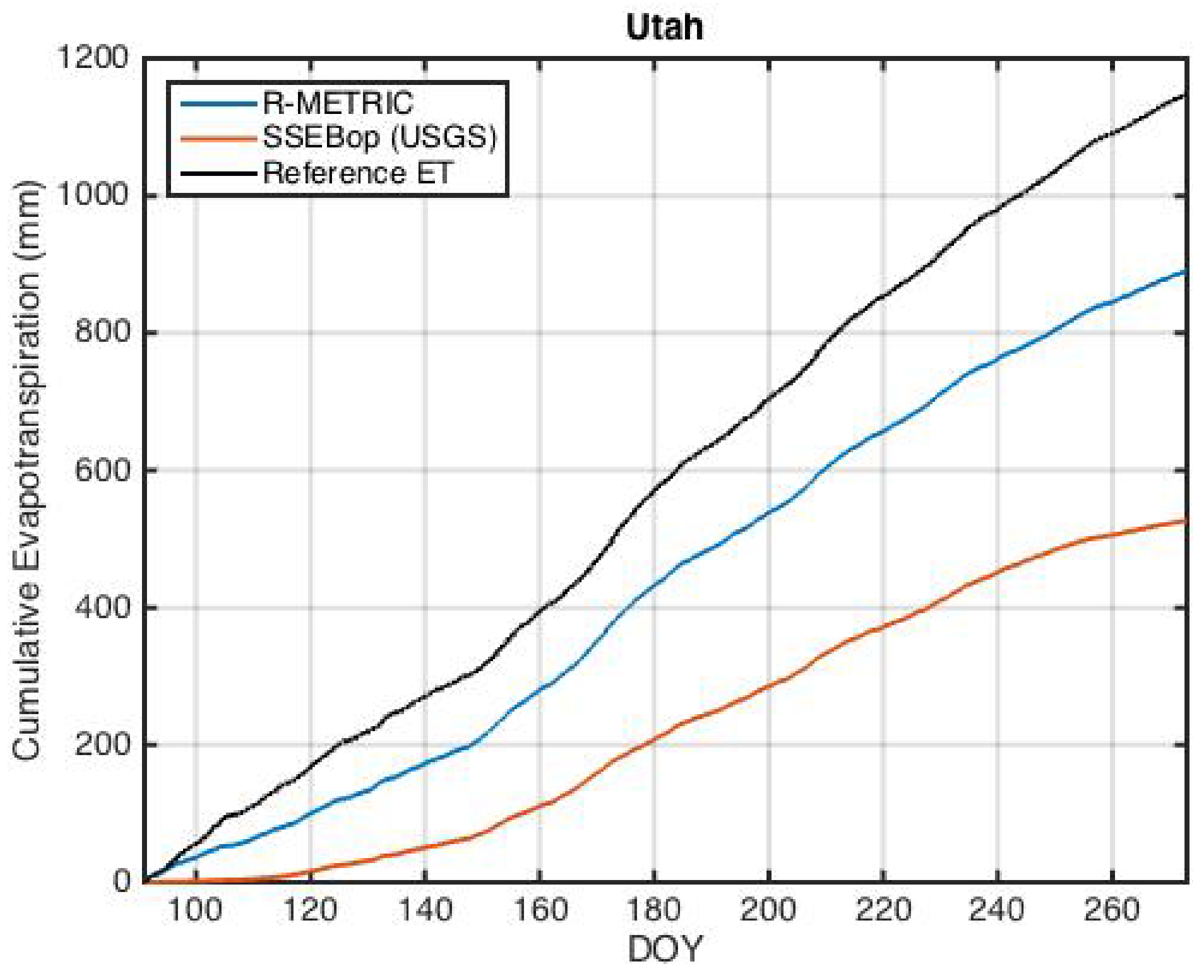

Figure 4-11 Cumulative seasonal ET estimated using the USGS SSEBop and R-METRIC remote sensing methods; Penman-Monteith ET for a reference alfalfa surface using the Pleasant Valley weather station data is included for comparison

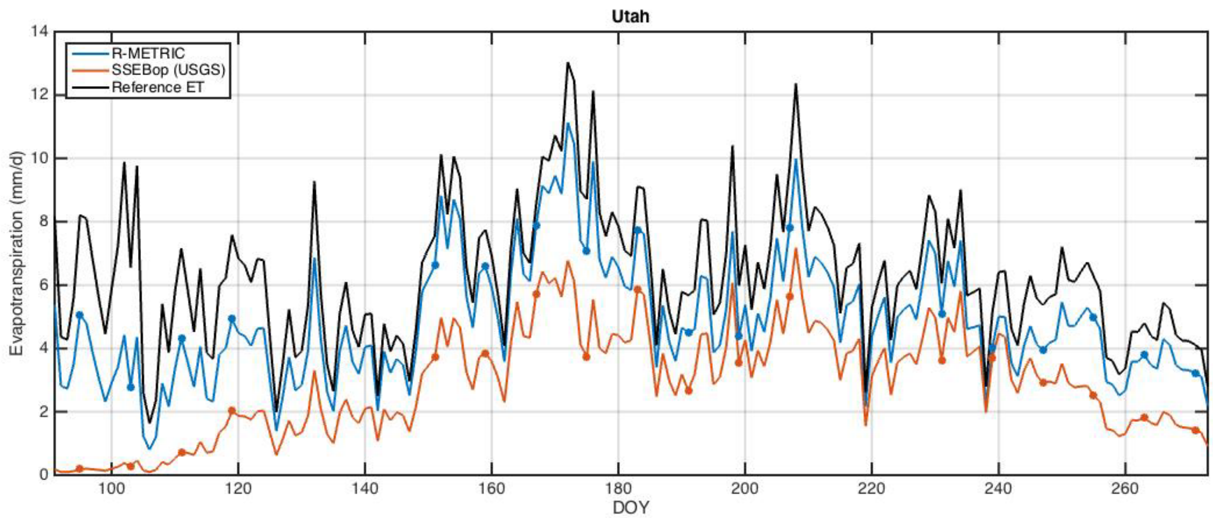

Figure 4-12 Average daily ET throughout the 2015 growing season for all irrigated lands in the Utah area of interest estimated using the USGS SSEBop and R-METRIC remote sensing methods; Penman-Monteith ET for a reference alfalfa surface is included for comparison

The Wyoming area of interest's spatially-explicit cumulative ET is shown in Figure 4-13. The cumulative seasonal ET (Figure 4-14) shows a large difference between R-METRIC and SSEBop (USGS), with R-METRIC producing the larger estimate. Daily means show that SSEBop (USGS) was much lower particuarly at the end of the growing season (Figure 4-15). The scenes used are indicated as circles.

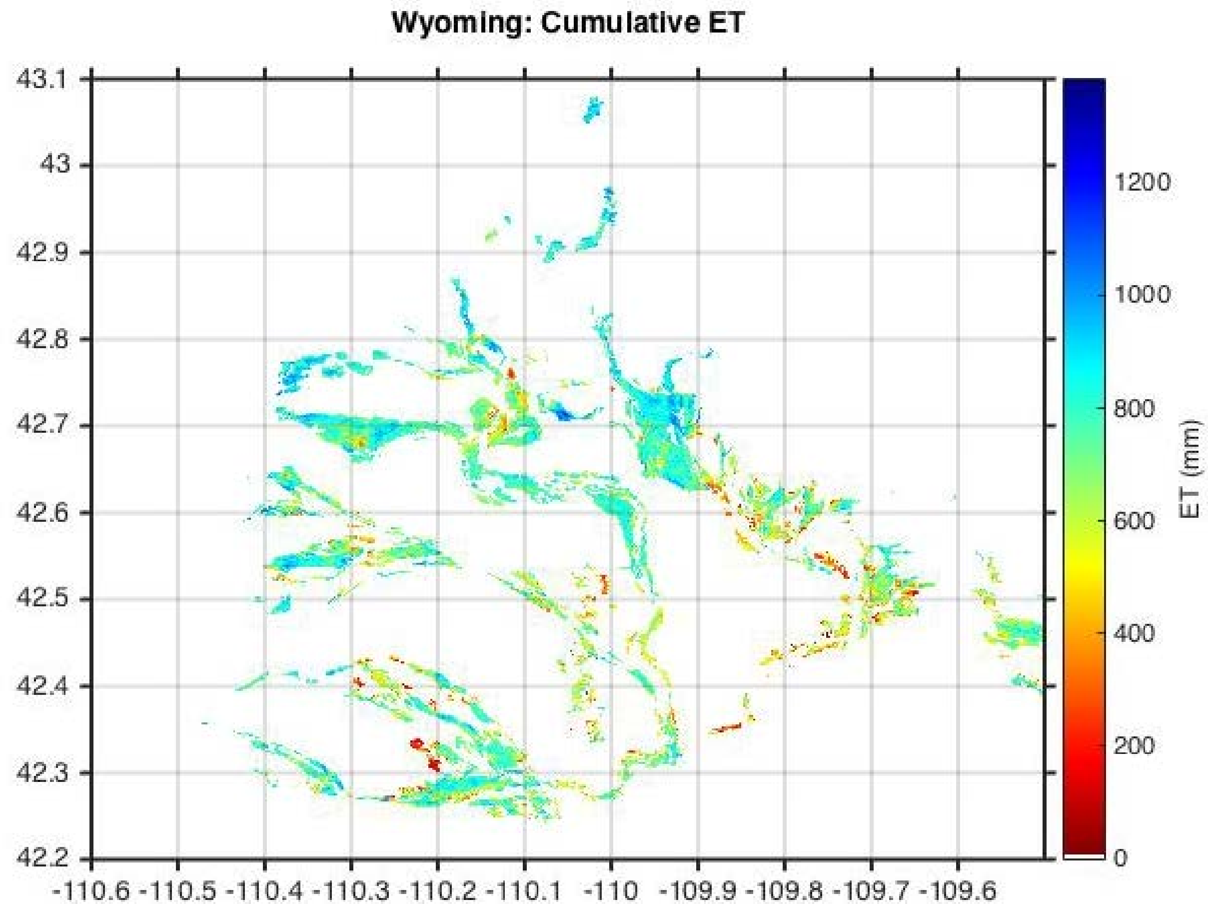

Figure 4-13 Cumulative seasonal ET for the 2015 growing season for the Wyoming area of interest estimated using the R-METRIC remote sensing method (gridlines indicate latitude and longitude)

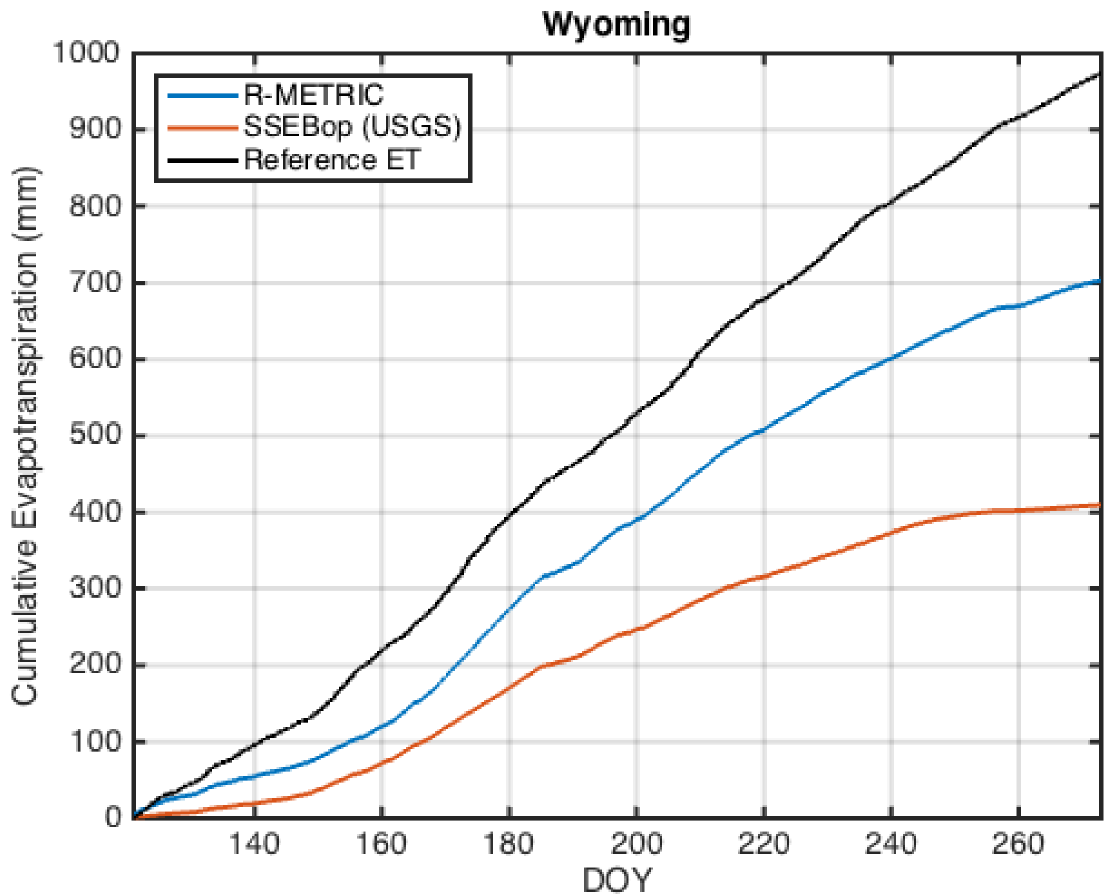

Figure 4-14 Cumulative seasonal ET estimated using R-METRIC and the USGS SSEBop remote sensing methods; Penman-Monteith ET for a reference alfalfa surface using Boulder weather station data is included for comparison

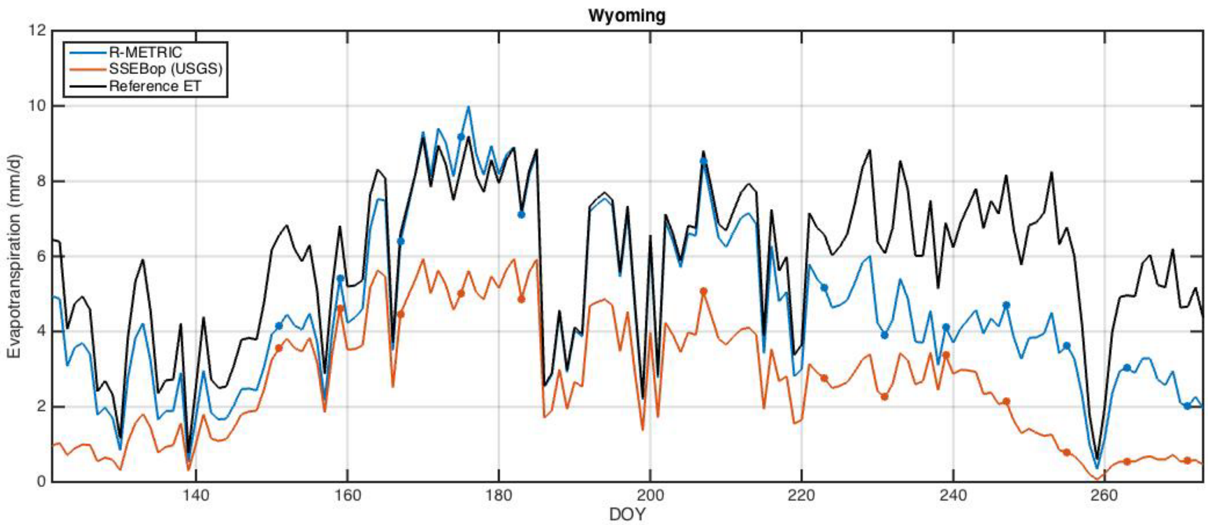

Figure 4-15 Average daily ET throughout the 2015 growing season for all irrigated lands in the Wyoming area of interest estimated using the USGS SSEBop and R-METRIC remote sensing methods; Penman-Monteith ET for a reference alfalfa surface is included for comparison

4.6 CALCULATION OF EVALUATION METRICS

4.6.1 Daily RMSE Calculation for EC Tower Comparison

RMSE was calculated using MATLAB's linear regression model. The formula for RMSE is:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \qquad (4)$$

where n is the number of observations, y_i is the observed ET at the EC tower for a given day, and $\hat{y}_i$ is the remote sensing ET for a given day.

4.6.2 Coefficient of Determination for Remote Sensing Measurements versus EC Tower Fluxes

The coefficient of determination, or R^2, is given by:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \qquad (5)$$

where $\bar{y}$ is the mean of the observed data.

In closing, the Upper Division States, UCRC, and Reclamation will make decisions regarding the Extended Climate Stations, EC towers, and remote sensing methods presented in Sections 2, 3, and 4 of this report, respectively. The final MOU concerning the UCRB and the installation and maintenance of consumptive use instrumentation is included in Appendix B.

As the Project progresses, the Study Team needs to confirm the list of land owners interested in having an Extended Climate Station on their land, finalize land access agreements, schedule equipment installation, and train owners in maintenance procedures. A decision will need to be made regarding whether replacement parts will be stocked. Additionally, physical infrastructure selection needs to occur such as sensor selection and procurement, and data collection procedures, to include configuring reliable telemetry of the raw data to reduce data loss and site visits, need to be finalized. Additionally, a survey of the immediate areas surrounding the proposed EC towers needs to occur prior to setup by an EC expert to finalize site selection.

This Project was aimed at characterizing the operational aspects of applying remote sensing to the evaluation of state-wide and ultimately region-wide ET from irrigated areas in the UCRB. A lot was learned about the practicalities of various methods, as well as what methods were ready for application during the 2015 growing season and which were not. Computing and human resources have been outlined as well as supporting databases, particularly with respect to meteorological data.

Within the constraints of this Project, only one ground site with measured evaporative flux using the EC technique to compare the remote sensing estimates was possible. This grass site near Rifle, Colorado represented a region that comes under some water stress through the growing season, as was clearly the case in 2015, and was representative of many irrigated regions in the UCRB. The results of R-METRIC, SSEBop (USGS) and variations of SSEB were tested against the EC flux data. However, ultimately these results come from one site with one predominant vegetation cover, climate, and soil type. The amount of scatter and bias in some of the results was unexpected.

The results of R-METRIC and SSEBop (USGS) were tested against the EC flux data (the results of other variations of SSEBop run by Reclamation are described in Appendix F.

Moving forward, the following actions are recommended:

- Collect preliminary wind roses prior to installation of EC towers. These data will be used to determine the predominant wind directions to minimize data loss due to the tower shadow.
- Address safety of crews going into the field, which may include training, development of risk management/safety plans, and issuance of personal protective equipment.
- Assess the available options to minimize and prevent, to the extent possible, potential failure modes of EC data collection.
- Decide on the approach that will be used for data analysis and processing.
- Implement a centralized server, with regular backups, for data archival.
- Hire personnel that have the suggested skills to carry out the work noted in this report.

- Efforts to apply remote sensing methods to the evaluation of consumptive water use by irrigated crops throughout all irrigated regions of the states in the UCRB should proceed. This work can proceed on a state-by-state basis or a region-wide effort.
- Choose one representative site in each state for the location of an EC tower flux measurement ground site. Such a network of EC towers would give personnel from each state the experience of working with these types of data within their state and would increase the number of sites and conditions with which to evaluate the remote sensing methods by a factor of four, including perhaps, methods not tested in the current Project.

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Appendix A

Meeting Minutes and Call Notes

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Appendix A
Meeting Minutes and Call Notes Listing

- Memo on Upper Basin Agricultural Study – Phone Notes, Erin Wilson, Wilson Water Group, October 27, 2014
  - *Attachment: Quality Assurance Procedures for Reclamation's Agrimet Weather Station Network, by Peter L. Palmer and Jama L. Hamel, No Date*
- Memo on Upper Basin Agricultural Study – Meeting Notes from CoAgMet Site Visit, Kara Sobieski, Wilson Water Group, October 28, 2014
- Updates on Climate Station and Eddy Covariance Tower Placement, Teleconference Meeting Notes, URS, November 17, 2014
  - *Attachment: Upper Colorado Basin Agricultural Water Consumptive Use Study – Phase II, Conference Call Notes, URS, October 24, 2014*
- Eddy Covariance Tower Siting, Field Meeting Notes, David Merritt, URS, November 21, 2014
- Memo on Upper Basin Agricultural Study – Meeting Notes, Erin Wilson, Wilson Water Group, February 3, 2015
- Phase II: Climate Station Locations and Progress Update, Conference Call Notes, URS, February 10, 2015
  - *Attachment: Memo on Upper Basin Agricultural Study – Recommendations for Extended Climate Station Siting, Erin Wilson and Kara Sobieski, Wilson Water Group, February 6, 2015*
- Phase II: Climate Station Locations, Eddy Covariance Station, and Progress Updates, Conference Call Notes, URS, May 5, 2015
- Phase II: Climate Station Locations and Progress Update, Conference Call Notes, URS, June 23, 2015
  - *Attachment: Informational Update on Colorado Tower Operations, Dr. Chad Higgins, Oregon State, June 19, 2015*
  - *Attachment: Memo on Current Status of Remote Sensing Project , Dr. Richard Cuenca, Hydrologic Engineering, Inc., June 18, 2015*
- Phase II: Climate Station Locations, Eddy Covariance Station, and Progress Updates, Meeting Notes, URS, August 24, 2015
  - *Attachment: Agenda, Estimation of Actual Evapotranspiration, URS, August 24, 2015*
  - *Attachment: Eddy Covariance Tower Footprint Analysis, Dr. Chad Higgins, Oregon State, No Date*
  - *Attachment: Draft Outline: UCRBC Remote Sensing Report, Dr. Richard Cuenca, Hydrologic Engineering, Inc., No Date*
- Estimation of Actual Evapotranspiration, Meeting Notes (with Attachments A, B, and C), URS, October 5, 2015
- Review of Preliminary Memorandum of Agreements for the Upper Colorado River Basin, Conference Call Notes, URS, October 19, 2015
- Review of Draft Memorandums of Understanding for the Upper Colorado River Basin, Conference Call Notes, URS, November 16, 2015
- Preparation for December 2, 2015 Meeting with the Upper Colorado River Commission, Conference Call Notes, URS, November 30, 2015

- Phase II: Progress Update, Conference Call Notes, URS, February 23, 2016
    - *Attachment: Agenda, Progress Update, URS, February 23, 2016*
    - *Attachment: Weather Station Siting, ASCE-EWRI Task Committee Report, January 2005*
    - *Attachment: AgriMet Site Visit Report, No Date*
    - *Attachment, AgriMet Field Calibration Sheet – CR1000*
    - *Attachment: [Remote Sensing] Executive Summary, No Date*
    - *Attachment: Report and Recommendations on Remote Sensing PowerPoint Presentation, Dr. Higgins, Hydrologic Engineering Inc., No Date*

Memo

To:	Dave Merritt, URS
From:	Erin Wilson
Date:	10/27/2014
Re:	Upper Basin Agricultural Study - Phone Notes

Jim Prairie organized a phone conversation on October 10, 2014, that included Jama Hamel of Reclamation and Nolan Doesken, Colorado State Climatologist.

- Jama Hamel is the AgriMet Program Coordinator. Her responsibilities include website programmer, field tech, and "budget person." AgriMet stations currently owned and operated by Reclamation are in Washington, Oregon, Idaho, Montana, and Nevada. Additional stations in Nevada are operated in cooperation with the Desert Research Institute and Reclamation, and additional stations in Utah are operated with the Utah Climate Center and Reclamation.
- AgriMet is considered the flagship for ET networks based on quality and maintenance of equipment and QA/QC of data collected.
- Nolan Doesken heads Colorado's CoAgMet network.

Climate Station Siting

- Jama indicated their primary criteria for siting new climate stations is user-driven based on requests from land owners directly or through cooperating agencies. She termed it a "Non-ideal" network of locations because of this. The landowners often become the permanent "observer" required for each station.
- A primary goal is to eventually have a least one station for every Landsat scene.
- Nolan indicated that CoAgMet climate station locations are also driven by user requests and, in some cases, they have installed climate stations in areas that are not particularly useful (e.g., in the middle of an orchard).
- When asked what their ideal criteria would be if they could dictate the locations of their stations, both Jama and Nolan agreed:
    - At least one in each satellite scene.
    - Located in key growing regions.
    - Located without prevailing wind obstacles (distance from obstruction needs to be 10 times the height of obstruction; if corn is 7-feet tall, the station needs to be 70 feet from the field).
    - Ideally in an alfalfa field with a great supply.

- We discussed the difficulties of using a more standard correlation approach to siting stations based on the non-contiguous nature of Upper Basin irrigation – they agreed that this approach cannot be accurately used in our study area.

<u>New Climate Stations and Partnerships Currently Contemplated</u>

- AgriMet has recently taken over the Utah State climate stations.
    - Upgraded the stations to AgriMet standards.
    - Taken over recording and data QA/QC.
    - Utah State will perform routine maintenance on all stations.
    - At this time they intend to add two new stations in the Colorado River Basin – one near Moab and one north of Glen Canyon area. Roger Hansen with Reclamation (Provo Office) is working with Utah State to locate the new sites.
    - The contact with Utah is Jobie Carlisle, Research Tech at the Utah Climate Center (office 435-797-7326; cell 435-881-2243). He is starting discussions about additional sites in Utah, potentially in Emery County. J. Humphreys is his contact with Emery County. Note that Jobie is also a good contact for Eddy CoVariance Towers.
- Jama indicated that David Dubois, New Mexico State Climatologist, is very interested in joining forces and including his network in the AgriMet system. (office 575-646-2974; email dwdubois@nmsu.edu).
- Jama indicated that AgriMet inherited some NOAA stations. She looked into retrofitting the existing NOAA stations and decided it was a logistical nightmare (so decided against). The difference in cost for a new station vs a retrofit was only about $1,000. The savings was not worth the difficulties associated with the data interaction agreement.
- Jama and Nolan are also discussing the possibility of AgriMet managing CoAgMet data; specifically performing QA/QC and serving the CoAgMet data on the AgriMet website. CoAgMet data would still need to be available through the CoAgMet site, but they currently only serve up "raw data" and the QA/QC aspect through AgriMet is very appealing.
- Nolan indicated that there are funds for two to three stations through the Gunnison Roundtable. There may still be time to influence the location for these stations.
- Nolan also went through an exercise to determine a "wish list" for about 30 or more stations. He'll find it and send it to us.
- Jama indicated she understand there may be funding for climate stations on Tribal lands. She said Margaret Red Deer with the USGS in Flagstaff may be a resource.

<u>Climate Station Maintenance</u>

- There are currently approximately 70 CoAgMet stations in Colorado. Wendy Ryan does all the basic calibration and maintenance for every station. Generally each site has routine maintenance once per year unless the data indicates there is an issue.
- Jama indicated they generally use the ASCE Standards for instrument calibration and data QA/QC. She sent their Quality Assurance Procedures (attached).

<u>Climate Station Site Agreements</u>

- Most CoAgMet sites are operated based on a gentlemen's agreement allowing essentially unlimited site access – CoAgMet does not own the land. They are beginning to require site-license agreements that define site access. All stations are on private farms – no stations are on public land.
- AgriMet requires a simple agreement that requires that AgriMet personnel can access the site with 30-days' notice. This access agreement is required if the owner wants a station on their land. AgriMet stations are also primarily on private land. If the site is irrigated by a Reclamation Project, AgriMet charges a reduced maintenance fee back to Reclamation.

QUALITY ASSURANCE PROCEDURES FOR RECLAMATION'S AGRIMET WEATHER STATION NETWORK

Peter L. Palmer[1]
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ABSTRACT

Competition for limited water resources in the western United States continues to increase. In most western states, irrigated agriculture is the largest single consumer of water, so efficient irrigation water management can lead to considerable water savings. To this end, the U.S. Bureau of Reclamation (Reclamation) and Bonneville Power Administration (BPA) partnered to create a network of automated agricultural weather stations - called AgriMet - in the Pacific Northwest. These stations collect and telemeter the meteorological parameters required to model crop evapotranspiration (ET). The information is used by irrigation districts, farmers, resource conservation agencies, and agricultural consultants for irrigation scheduling and related purposes. The network consists of over 70 weather stations in the Pacific Northwest that telemeter weather data each hour via the Geostationary Operational Environmental satellite (GOES). Each station measures air temperature, relative humidity, solar radiation, wind speed, wind direction, and precipitation. Other stations have additional sensors, such as soil temperature, crop canopy temperature, leaf wetness, and diffuse solar radiation. Accuracy of the weather data is critical to successful crop water use modeling and other applications. Quality assurance for the AgriMet program consists of five interdependent components: laboratory sensor calibration, an annual maintenance and calibration visit to each weather station, automated data quality control procedures, manual data quality control procedures, and an annual review of weather and associated evapotranspiration parameters. These quality assurance efforts provide reliable meteorological and crop water use information for a variety of applications in the Pacific Northwest.

INTRODUCTION

In 1983, Reclamation partnered with BPA in an effort to promote efficient irrigation water use. This partnership resulted in the installation of a network of automated agricultural weather stations called "AgriMet" (for Agricultural Meteorology) in the Pacific Northwest. These stations collect and telemeter the meteorological parameters required to model crop evapotranspiration (ET). Since the initial installation of 3 stations in 1983, the network has grown to over 60 stations in Reclamation's Pacific Northwest Region, 22 stations in the Great Plains Region in Montana (east of the Continental Divide), and seven stations in the Mid Pacific Region. Reclamation has established partnerships with more than 25 entities, including other federal and state agencies, soil and water conservation districts, universities, public utilities, and private businesses to help fund the operation of the AgriMet network.

AGRIMET DATA COLLECTION AND TRANSMISSION

AgriMet stations are located in agricultural areas throughout Idaho, Montana, Oregon, and Washington, with additional stations located in northern California, western Wyoming, and Nevada (Fig. 1). The stations are typically located on the edge of irrigated fields so that the observed weather data approximates the meteorological conditions affecting the cultivated crops in the area (Fig. 2). Each AgriMet station is configured with a standard set of sensors, including air temperature, precipitation, solar radiation, wind speed and direction, and relative humidity. These standard sensors measure the meteorological parameters required for modeling crop ET. Some sites have special sensors, including soil temperature, diffuse pyranometers for special solar radiation studies, crop canopy temperature, leaf wetness, and evaporation pan sensors.

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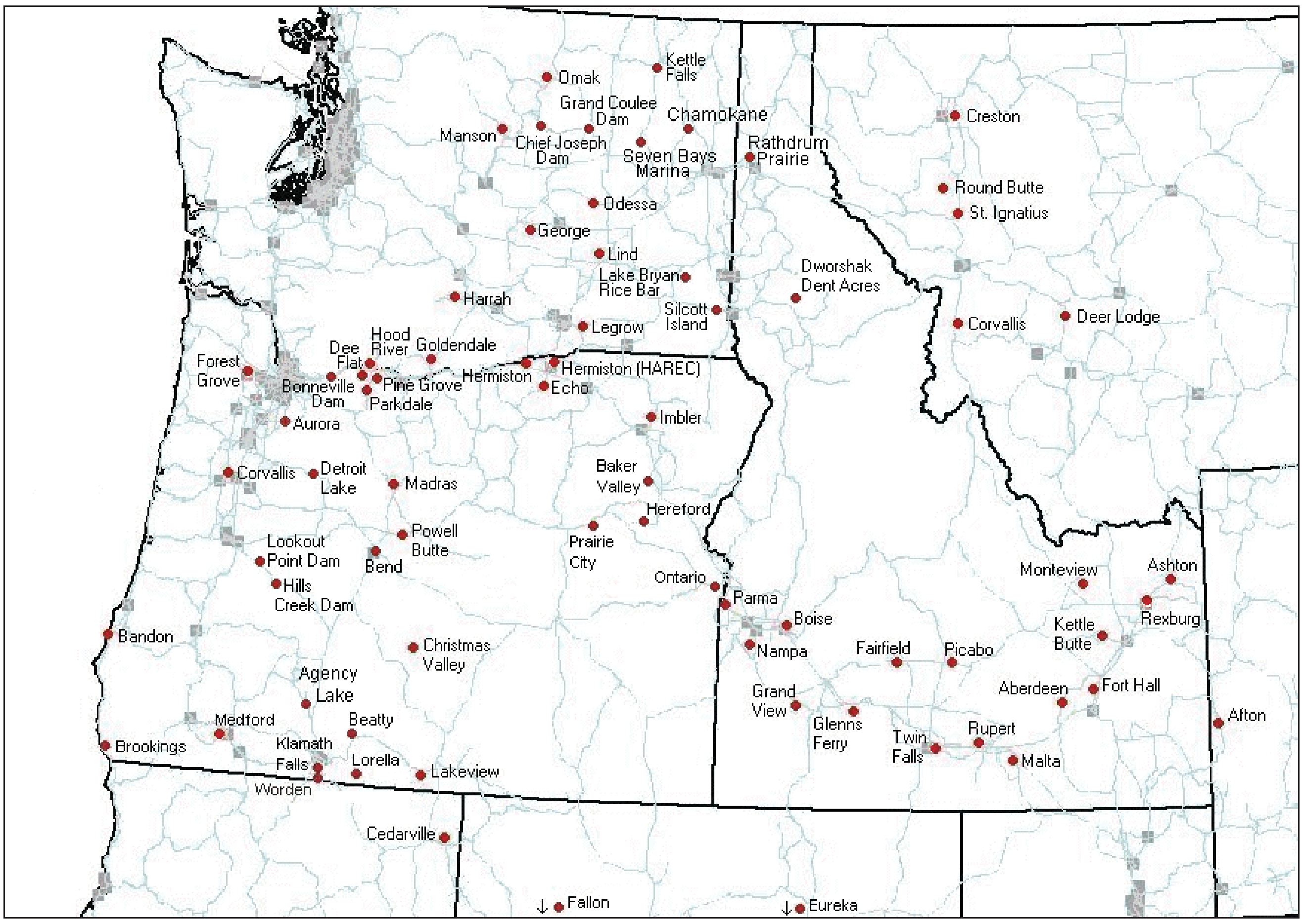

Figure 1. AgriMet weather station locations in the Pacific Northwest Region.

All the weather station components, including sensors, solar panel, antenna, data logger, and transmitter are mounted on a sturdy aluminum tripod. Sensors are mounted at standard sensor heights for agricultural weather data collection requirements. Wind, air temperature, relative humidity, and precipitation are measured at 2 meters above the ground surface. Power for each weather station is provided by a heavy-duty lead acid storage battery that is recharged daily by a solar panel.

The data logger at the site monitors each of the sensors once every second. These readings are used to derive the final data parameters for subsequent transmission, such as 15 minute air temperature observations, total hourly precipitation, average wind speed, etc. These parameters are transmitted once an hour via the GOES satellite (Geostationary Operational Environmental Satellite) to a receive site at Reclamation's Pacific Northwest Regional Office in Boise, Idaho. The receive site also down-links data for other Reclamation programs, as well as for other cooperating federal agencies.

Figure 2. Typical AgriMet weather station.

Evapotranspiration estimates, as well as any other product derived from meteorological data, are only as good as the data that goes into the computation. To ensure a high quality meteorological data set, the AgriMet program has developed a stringent set of quality assurance procedures. These procedures have evolved over time as improved equipment and more powerful computers and graphics capabilities became available.

Quality assurance for the AgriMet program consists of five interrelated components: laboratory calibration of weather sensors, an annual maintenance and calibration visit to each weather station, automated data quality control procedures, manual data quality control procedures, and an annual review of weather and associated evapotranspiration parameters. Each of these components is discussed in detail below.

LABORATORY CALIBRATION OF WEATHER SENSORS

Good data quality begins with accurate, reliable sensors in the field. In order to minimize station downtime and to respond rapidly to sensor failures, vandalism, or other problems, the AgriMet network maintains approximately a ten percent overstock of spare sensors and components. These sensors and components are maintained in a calibrated state for use anytime during the year, or for sensor replacement during annual site maintenance and calibration visits.

Before each calibration season, an AgriMet technician calibrates a designated bench standard Vaisala HMP 45D relative humidity sensor using a two salt (LiCl and NaCl) calibration process. Each salt has a known humidity when mixed at saturation with water depending on surrounding air temperature (LiCl 11.3 percent and NaCl 75.3 percent, at 75°F). The Vaisala output for each salt solution is adjusted as needed to reach the desired output. The temperature output is also verified using an analog thermometer.

Several solar radiation sensors (Licor LI-200 pyranometers) are also pre-calibrated using the procedures detailed in the field calibration section below. These pre-calibrated spares are necessary in case field replacement is required when solar conditions are not conducive to an on-site calibration.

FIELD CALIBRATION AND MAINTENANCE OF WEATHER STATIONS

All AgriMet sites receive an annual maintenance and inspection visit by Reclamation technicians in the spring that includes calibration and maintenance of all sensors. All sensors are compared against laboratory calibrated standards and are adjusted or replaced as needed.

Data logger and transmitter parameters are checked for conformance to specifications. System battery voltage, solar panel output, and voltage regulator output are checked; these items are replaced or adjusted as needed. Batteries are replaced every 6 years to decrease the chance of mid-winter failure. All sensors are compared against laboratory calibrated standards and are adjusted or replaced as needed. Sensor replacement is tracked using a custom site visit database to identify possible repeat problems with sensors and sites. This special attention given to the sites during these annual calibration and maintenance visits provides early detection of problems and greatly reduces station or sensor failure during the year. Sensors deployed in the field require annual on site calibration, maintenance and cleaning as described below.

<u>Solar Radiation Sensors</u>: The AgriMet program uses a Licor LI-200 pyranometer for solar radiation measurement. Every 2 years, AgriMet sends 2-3 Licor pyranometers to the National Renewable Energy Laboratory (NREL) in Golden, Colorado for calibration against a NIST traceable standard. This is part of NREL's "Broadband Outdoor Radiometer Calibration - BORCAL" program (Myers et al, 2002). This provides AgriMet technicians with a solar radiation standard to use for field calibrations. In the field, a temporary mast is assembled on the station tripod and the lab standard pyranometer is mounted adjacent to the station pyranometer. A Campbell Scientific CR10x data logger with a custom calibration program is used to make paired measurements of the two pyranometers on a one second interval. After approximately 1 hour (3600 paired observations), the results of the calibration are entered into a spreadsheet which computes the output of the station pyranometer (in millivolts of output per 1000 W/m2 of solar input). The technician then compares the results of the calibration with the previous year's solar radiation values using the clear-sky solar radiation (R_{so}) method, described below in the "Annual Data Quality Control" section, to verify the accuracy of the calibration. Although every effort is made to conduct station specific field solar calibrations, AgriMet maintains a set of "pre-calibrated" pyranometers for replacement of failed or aged sensors during site visits where weather conditions are not conducive to a solar calibration.

<u>Relative Humidity/Air Temperature Sensors</u>: AgriMet uses a modified Vaisala HMP35A and HMP45D relative humidity/air temperature sensor in its weather station network. The factory thermistor has historically been

replaced with a YSI Model 44030 thermistor for improved accuracy. In the field, the technician sets up two clean, dry radiation gill shields, one for the station sensor and one for the bench sensor. The technician then removes the filter cap of the station sensor and replaces it with a clean, dry filter. If the sensor is an HMP45D model, the o-ring sealing the two portions of the sensor is coated with high-vacuum grease to help resist corrosion on the pins. Both sensors are then placed in the provided shields and left for at least 15 minutes to equilibrate with surrounding conditions. The station shield is then cleaned to remove any dark spots or foreign substances that may absorb heat. The values of the station and bench sensor are then compared, and if the two are within 3 percent relative humidity, the sensor is returned to its original shield. If the two sensors are not within 3 percent of each other, the field sensor is replaced with a lab-calibrated sensor and again compared to the bench standard. In 2010, the AgriMet program intends to replace all existing humidity and air temperature sensors with new technology sensors (Rotronics Hygroclip2 S3). These sensors will be swapped out every 2 years and replaced with lab-calibrated sensors.

Wind Sensors: AgriMet utilizes the RM Young Model 05103 anemometer to measure wind speed and direction. The AgriMet technician removes the nose cone, checks the shaft play using a shim spacer, and the bearings using a torque disk. After listening for dirt while spinning the bearings, the nose cone is replaced and wind speed output verified using the RM Young Model 18802 Anemometer Drive. The motor in the drive rotates the anemometer shaft at a defined set of wind speeds ranging from 5 to 65 mph. If sensor output does not match the corresponding wind speed, the sensor is replaced (the sensors are extremely reliable and are yet to require replacement). These extraneous wind values are not included in the telemetered data through use of a special calibration flag. The technician then verifies wind direction by comparing sensor output with a compass reading set with the station's magnetic declination to measure true south. If the observed direction is greater than +/- 3 degrees, the technician realigns the sensor to match the output to the compass.

Precipitation Gages: AgriMet currently employs two types of precipitation gages, a tipping bucket (Hydrologic Services Model TB3) and a weighing device with a bucket containing an antifreeze/mineral oil mixture (24 inch load cell, 12 inch Belfort Instruments gage, and 20 inch Belfort Instruments gage). Tipping buckets are used where there is little frozen precipitation and high rainfall volumes; weighing gages are used where frozen precipitation is a significant portion of the total annual precipitation. Currently, the Belfort Instruments gages are in the process of being replaced with 24 inch load cell devices to increase storage capacity, dependability, and accuracy. Both types of sensors undergo a thorough cleaning of the mechanisms and a calibration check as described below.

> Tipping Bucket – Using a graduated cylinder, the technician measures out 798 ml of water into a special bottle designed to release the water at a slow, steady flow rate. The bottle is placed upside down in the precipitation catch portion of the sensor until the bottle is drained. The number of tips is then read from a special calibration location in the data logger and the device is adjusted if needed. If adjustment is required, the procedure is repeated. This "artificial" precipitation is not included in the actual station catch through use of a special calibration toggle flag.
>
> Weighing Device - Calibrating the load cell and Belfort gages both require removal of the outer shroud and weighing bucket. The technician places precision weights, equaling 1 inch of water each, one at a time on the weighing mechanism until the maximum water equivalent is reached (12, 20 or 24 inch). The output of the sensor is read with each plate and should show a one inch increase. If the error over the full range is greater than 3 percent, the sensor is adjusted and the procedure repeated.

The following sensors are non-standard sensors, installed at selected AgriMet stations depending upon local need:

Soil Temperature Sensors: A YSI Model 44030 thermistor soldered to a two conductor wire, and potted in potting compound measures soil temperature at various standard depths. The technician digs a hole in an area representative of where the station sensors are located, and inserts a digital thermometer into the soil at the appropriate depth to compare temperatures. Soil temperatures can be highly variable due to slight differences in vegetative cover, ground shading, depth, or other environmental factors. Because of this variability, the technician also graphically reviews previous data to ensure the sensors are behaving as expected (e.g., in the summer, temperature and diurnal fluctuation decrease with depth). Large temperature differences or other anomalies require replacement of the sensor.

Shelter and Canopy Temperature Sensors: Shelter and canopy temperature sensors are essentially identical to the soil temperature sensor and are similarly calibrated. The digital thermometer is placed next to the sensor and the values compared. The technician also looks at previous data compared with the station temperature to ensure they are closely plotting together. Anomalous readings also require sensor replacement.

Leaf Wetness Sensors: AgriMet uses an unpainted Campbell Scientific Model 237 leaf wetness sensor. At the site, the technician wets the face of the sensor and verifies the output drop from 6999 (completely dry) to about 0 (completely wet). The sensor is then wiped off and the technician verifies the return to 6999 output. Previous humidity data is also plotted against the leaf wetness values to verify response to humidity changes. Malfunction requires sensor replacement.

Barometer: To measure barometric pressure, AgriMet uses a Vaisala Model PTB 101B barometer. Onsite calibration is not feasible; therefore, barometric pressure values are plotted against values of proximal sites to verify similar responses to changes in atmospheric pressure. On initial installation and occasionally thereafter, station barometric pressure readings are verified against nearby National Weather Service reported values when barometric pressure values are consistent over large areas.

AUTOMATED DATA QUALITY CONTROL PROCEDURES

Weather data transmitted via the GOES satellite is subjected to a variety of automated quality control procedures immediately upon receipt. These validation tests include a check of satellite transmission data quality parameters, upper and lower value limit tests, and rate of change tests. If the incoming data fails any of these checks, it is marked with a flag indicating the nature of the failure before being added to the database. These flagged values are not used in subsequent calculations, such as computation of average daily temperatures or daily ET rates. After these automated quality control processes are completed, the 15 minute (and hourly) data are stored in a "dayfiles" database. Standard AgriMet dayfile parameters include instantaneous air temperature and relative humidity, computed dew point, peak wind gust, and average wind speed and wind direction -- all on 15 minute intervals. Hourly data includes accumulated wind run, accumulated solar radiation, and accumulated precipitation.

Between 5:00 and 5:30 am each morning, several automated processes run on the dayfiles data, producing summary parameters for the previous day, including daily maximum, minimum, and average air temperatures, total daily wind run, average wind direction, peak wind gust, total daily precipitation, total daily solar radiation, mean relative humidity, mean dew point, and reference ET. For stations with special sensors, other summary parameters are generated, such as mean 4-inch soil temperature. These data are stored in an "archive" database. All of the historical weather information (both hourly/15 minute and daily summaries) is available on the AgriMet website for the period of record.

MANUAL DATA QUALITY CONTROL PROCEDURES

In addition to the automated checks, a manual quality control review is performed on the data each working day. These procedures include review of satellite transmission quality parameters that may point to data quality problems not detected by the automated procedures. Other checks include graphical review of sensor data by groups of sites that have similar climatic characteristics. Apparent anomalies are examined for possible data quality problems, and bad data are removed or estimated. Archive parameters and ET values are then recalculated using the revised data. These changes are reposted to the AgriMet website. AgriMet's quality control procedures result in a very complete, accurate, and timely database of meteorological information, easily available on the Internet.

In the early days of the AgriMet program (the mid-1980s), data quality assurance procedures were rudimentary and limited to manual review of tabular archive data. The sheer volume of dayfile data prevented close inspection of this data set (e.g., there are 96 temperature, humidity, and wind speed observations for each station each day). With only a few weather stations in the network, this methodology was fairly effective, although tedious. As more stations came on line and the volume of data increased, new procedures were developed. Automated techniques were implemented to scrutinize weather data based on upper and lower limits and rates of change between successive observations. Customized graphics programs were developed to plot archive weather data from climatically and geographically similar weather stations.

Early each workday morning, an AgriMet technician reviews the results of the automated data quality control procedures that were generated for the previous calendar day, paying particular attention to the satellite transmission statistics. Items that are reviewed include:

- Number of transmissions received (24 hourly transmits are expected)
- Message length (truncated or interfered transmissions may contain data errors)
- Parity bit check (a technique to insure correct decoding of data)
- Evaluation of transmit power and frequency (to insure compliance with GOES policies)
- Evaluation of station battery voltage (for early warning about potential power supply problems)
- Difference between expected and actual data transmission time (indicates clock drift)

After the satellite statistics are reviewed, the technician then reviews a list of various weather parameters, sorted by magnitude for all weather stations in the network, to quickly find potential outliers. Parameters reviewed include evapotranspiration, total solar radiation, and 24-hour wind run. At any point in the review of satellite and weather data parameters, the technician may "dig deeper" into any potential anomaly to correct any errors.

Next, the technician reviews a list of files that are generated on the AgriMet database system for publishing on Reclamation's web server. The time and date stamps and number of files provide assurance that all the various weather and crop water use products are generated according to an expected schedule. Process log files are automatically searched for key words that could indicate problems. The system queue is reviewed to insure that all required processes are correctly scheduled for execution. Finally, a quick spot check of web site content is conducted to insure that the publication of time sensitive products is up to date.

The final step in the quality control procedure is the graphical review of daily and selected hourly weather parameters. In previous years, AgriMet used a set of custom developed graphics to plot and review weather data from a group of stations that were climatologically and geographically similar. For example, maximum daily air temperature for the last week for seven stations in the Upper Snake River Plain in Idaho would be graphed together. This technique allows for rapid identification of outliers or potential anomalies.

In 2008 AgriMet developed a new set of graphical procedures using an Excel spreadsheet and visual basic programming. Previously, custom graphic programs were loaded on computers requiring Virtual Private Network (VPN) or direct network access, resulting in limited use away from office workstations. An Excel spreadsheet, developed by the AgriMet technician, mimics the basic concepts of the previous software. The new spreadsheet process incorporates data previously not reviewed on a daily basis, improving data quality assurance. The spreadsheet only requires Excel and internet access, allowing for easy accessibility to this portion of the quality control procedures. Visual Basic programming commands import data into a spreadsheet from the AgriMet web site, calling various sub routines based on the site and parameter. The spreadsheet includes date, station and parameter references, a worksheet for each region, and imported numerical data and graphical procedures for each worksheet (Fig. 3). A command button loads date specific data into the spreadsheet, updating both the numerical data and associated graphics. The graphs of the different weather parameters for each group are viewed on the same worksheet, resulting in better comparison of data in a shorter amount of time.

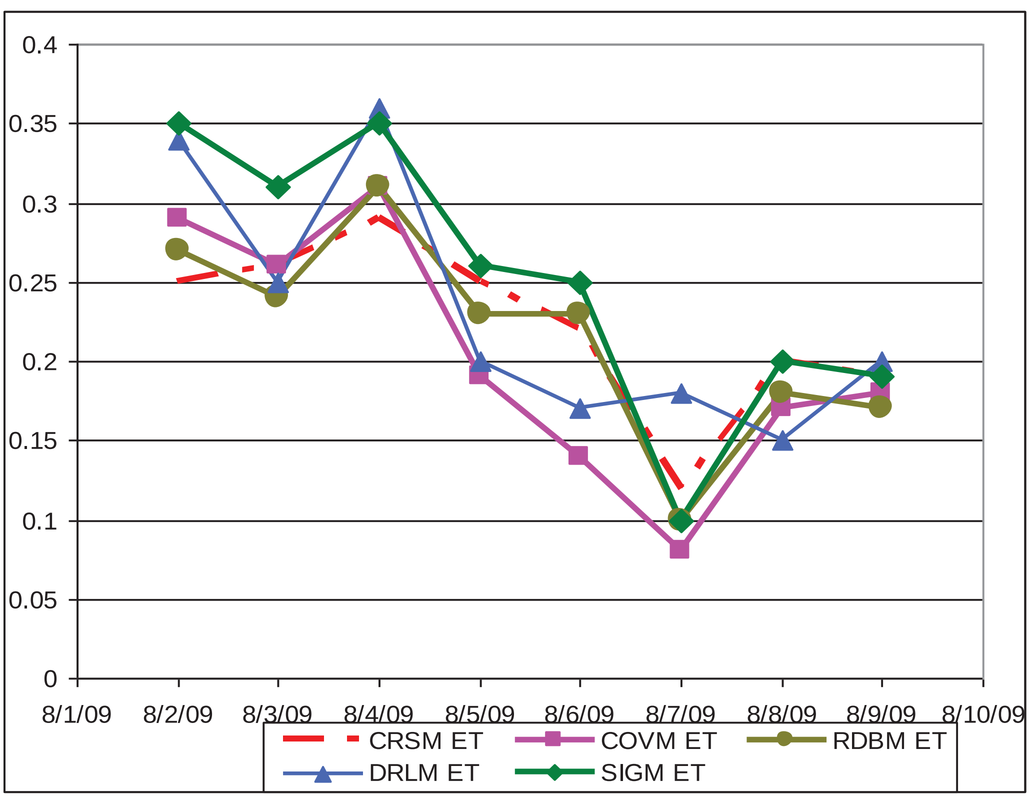

Figure 3. Example of graph for daily review of weather parameters.

ANNUAL DATA QUALITY CONTROL PROCEDURES

At the conclusion of each year, an AgriMet technician reviews annual graphs of weather data and crop consumptive water use in both climatologically and geographically similar groups, as well as individually. Reviewing historical data provides an overall picture of how a particular year compares to other years and allows for quick identification of data errors that may have been previously overlooked.

Yearly Data Analysis: Excel spreadsheets import weather data for the entire period of record and display the data graphically (Fig. 4). Outlying data points are investigated and edited if needed, or a note is made within the spreadsheet with an explanation of each outlier. For example, the 107 degree day in Figure 4 would stand out as a suspect data point for a coastal location like Brookings, Oregon. However, field technicians calibrated the station on that day and verified the temperature values. Had they not been present, the technician would review the 15 minute values for that day for a gradual increase to that temperature and then also verify it with other local observations.

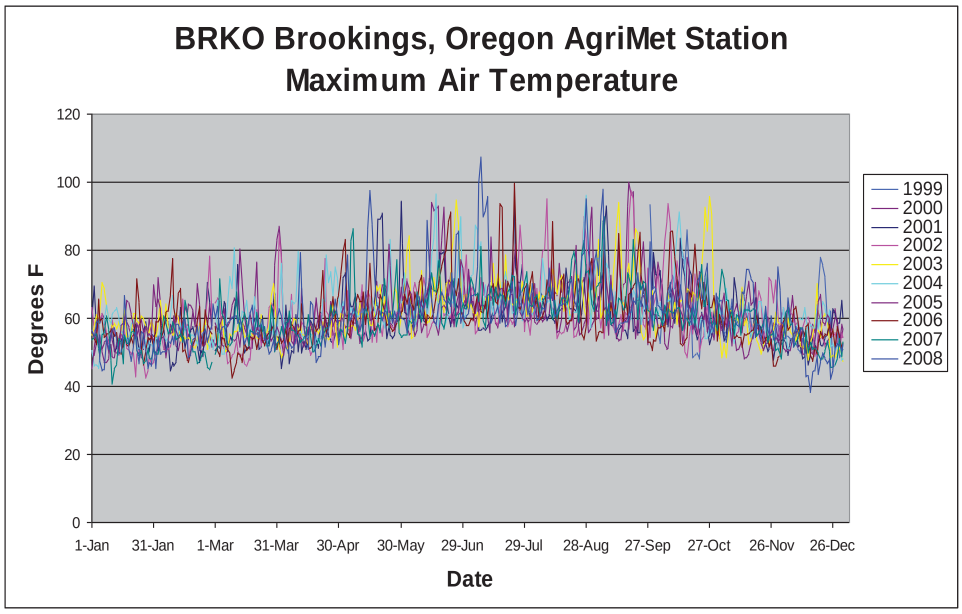

Figure 4. Example of annual graph for review of maximum air temperature.

Crop Consumptive Water Use: Total annual crop consumptive water use is also entered in a spreadsheet and the complete historical record is graphed (Fig. 5). All the crops that are modeled for each station are displayed on the graph. This technique quickly identifies any errors in annual totals of crop water use, and also allows for a quick comparison between years.

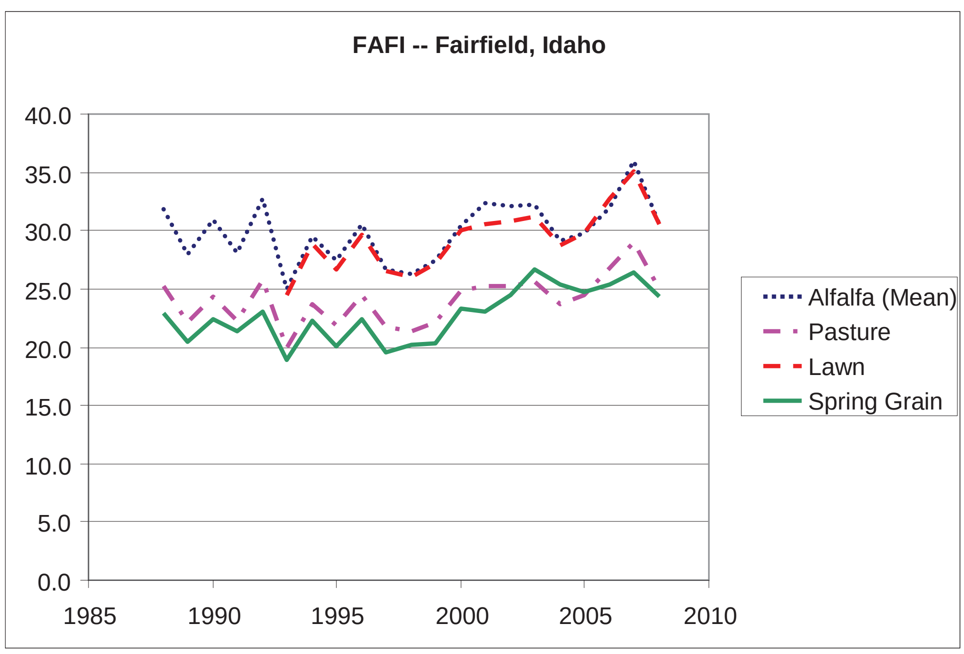

Figure 5. Example of annual graph of crop consumptive water use.

Clear-Sky Solar Radiation (Rso): After completion of the annual solar calibration (described in the Field Calibration and Maintenance of Weather Stations section), the technician compares the solar calibration results with computed clear-sky solar radiation. Clear-sky solar radiation is an estimate of the radiation the site would receive under cloud free conditions for any given day of the year. It is computed using the site elevation and latitude, as well as mean dew point temperature that provides an indicator of solar attenuation due to water vapor in the atmosphere (EWRI 2005).

Observed daily solar radiation and mean dew point temperature for each AgriMet station are automatically loaded into a spreadsheet using the Visual Basic procedure described in the Manual Data Quality Control Procedures section. The spreadsheet calculates an estimate of clear-sky R_{so} using two methods (Method A and Method B). Method A only considers extraterrestrial radiation and elevation, while Method B also includes mean dew point temperature as a water vapor parameter. Method A, Method B, and the observed solar radiation values are each plotted and compared on a graph to determine if an adjustment to the solar calibration scale factor is needed (Fig. 5). The clear-sky R_{so} method is extremely effective for both annual review of calibration results and investigation of suspect solar radiation values found during the manual data quality assurance routine.

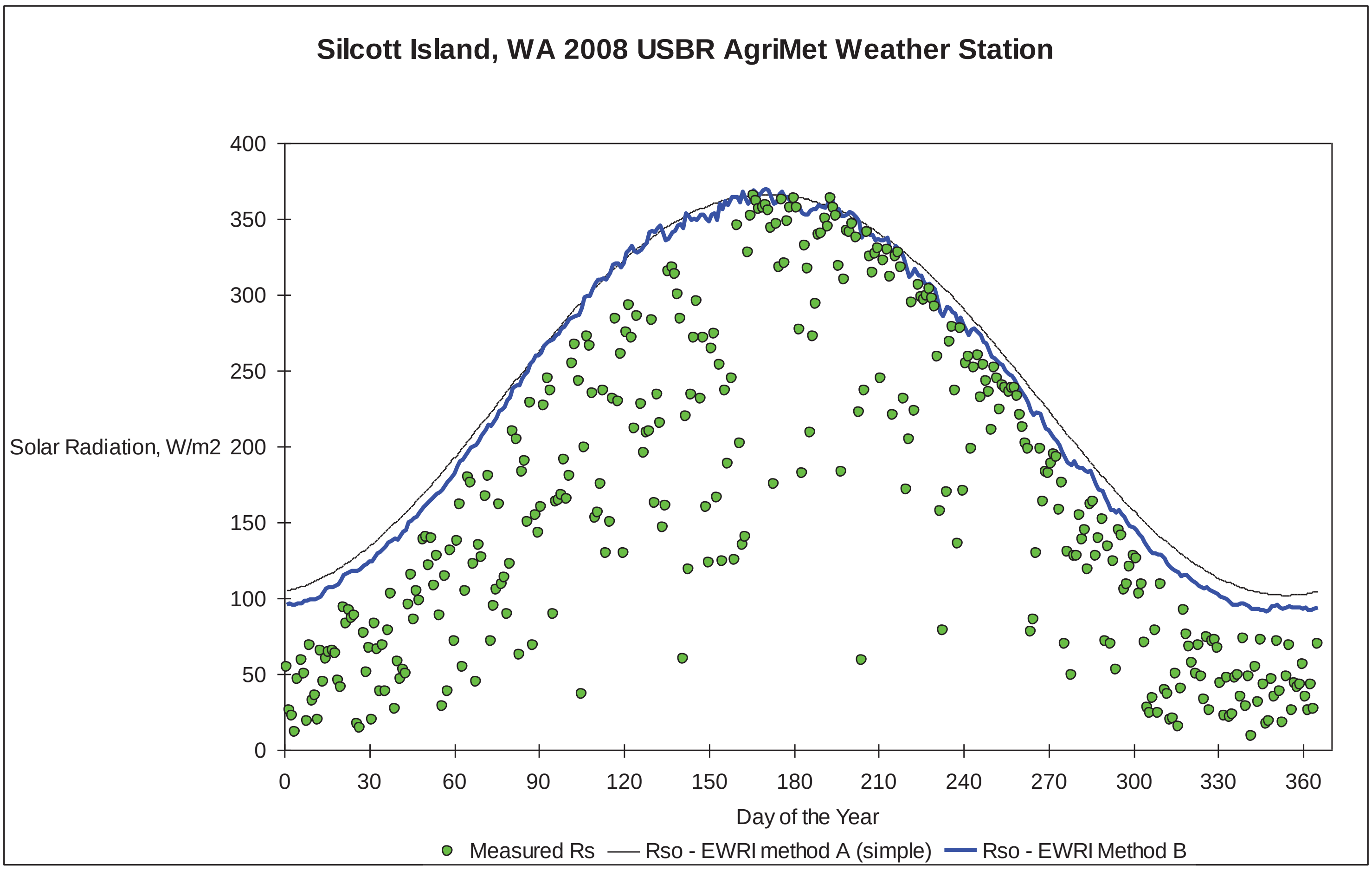

Figure 5. 2008 R_{so} plot for Silcott Island, Washington shows results of a solar calibration adjustment at approximately day 160. Prior to the adjustment, all of the observed solar readings were below the calculated clear-sky solar radiation. Observed readings after the adjustment fit the predicted curve much better. Observed values that lie well below the clear-sky curves are for days with varying amounts of cloud cover.

USES OF AGRIMET PRODUCTS AND INFORMATION

AgriMet crop water use information is integrated into various on-farm technical assistance programs by local agricultural consultants, the Cooperative Extension Service, and the USDA Natural Resources Conservation Service. As competition for limited water supplies increases - as well as the cost of pumping for irrigation - farmers are turning more and more to scientific irrigation scheduling.

The most common method for irrigation scheduling is known as the "checkbook method," accounting for deposits and withdrawals to the soil moisture balance. For this procedure, the farmer must first know the plant root depth and water holding capacity of the soil. This information is typically available from detailed soil surveys of the area, or from site specific soil tests. After each irrigation during the growing season, the farmer tracks the daily crop specific ET, available from AgriMet. When the cumulative water use equals the Management Allowable Depletion (MAD) for that crop, it's time to irrigate again. Specific knowledge of the irrigation system, combined with ET information from AgriMet, allows a farmer to apply the right amount of water at the right time for optimum crop production. Not only does the farmer realize savings in water and pumping costs, but reduced leaching results in reduced costs for fertilizer, herbicides, and pesticides. Various agricultural consultants have reported water and power savings ranging from 15 to 50 percent through the use of AgriMet supplied ET data (Dockter 1996). Some irrigators have reported real savings of as much as $25 per acre in pumping costs after using AgriMet ET data to schedule their irrigations (Palmer 2004). Indirect benefits of scientific irrigation scheduling include reduction in non-point source surface water pollution (through reductions in nutrient and chemical laden irrigation tail water) as well as protecting groundwater supplies through reduced leaching of agricultural chemicals.

AgriMet ET information is being extensively used by irrigators for on-farm irrigation water management. In a study conducted for the BPA, "on-line services, primarily AgriMet, are the most commonly used source for obtaining this (ET) information and account for 45 percent of cases. These figures, however, under-represent the actual use of ET information, particularly from AgriMet, since they do not take into account cases where commercial irrigation service providers provide this data" (Kema-Xenergy Inc. 2003).

Through scientific irrigation scheduling, AgriMet offers significant opportunities for irrigators to reduce their use of limited irrigation water supplies. There are financial incentives to do so, beyond just the costs of water and the power required to move it. For example, in a case study conducted by Oregon State University (English 2002), an economic analysis was conducted on a 125 acre center pivot of potatoes in Washington supplied by a pump with 700 feet of total lift. Assuming 19 percent excess water use (a typical value, according to the study), and a low sensitivity to the excess water (resulting in a 3 percent yield loss), the extra costs to the farmer included:

Energy Cost:	$ 1,490
Nitrogen Leaching:	$ 5,625
Yield Reduction:	$ 10,890
Total Cost:	$ 18,005

In the Lake Chelan area of Washington, the local irrigation district uses AgriMet data for site-specific irrigation scheduling (Cross 1997). Manual soil moisture measurements are taken weekly at 2-4 sites per orchard in over 60 fruit orchards in the area. Daily AgriMet data is used to monitor the crop water use between field measurements. The soil moisture is plotted on a time series graph, showing soil moisture content at several depths through the growing season. When the AgriMet ET data indicates that the soil moisture has dropped to the management allowable depletion level, the producer irrigates the orchard. The next field measurement shows the new soil moisture levels, and the daily consumptive use values from AgriMet are systematically subtracted from the soil moisture levels until the next irrigation is scheduled. This process is repeated throughout the growing season, and updated information is provided to each producer on the same day the soil moisture measurements are taken.

AgriMet weather data are used for a variety of applications in addition to ET computation, and requests for current and historical weather information from the AgriMet network are common. Agricultural producers depend on wind speed and direction for scheduling practices such as field burning and pesticide applications. Weather data is used by state agencies for investigating pesticide application and ground water contamination issues. The National Weather Service uses AgriMet weather data for short-term forecasting and forecast verification. Several electric utilities use the weather information to forecast daily energy requirements, including peaking power. University researchers frequently use AgriMet data for a variety of applications, ranging from regional consumptive water use modeling to locating new orchards. ET information is being used by other agencies, such as the National Resources Conservation Service, to document compliance with irrigation water management practices on individual farm tracts. Increasingly, ET information from weather station networks is being used in water rights management by state water resource agencies.

SUMMARY

In the early 1980s, Reclamation, in partnership with BPA, developed a network of automated agricultural weather stations in the Pacific Northwest. From the original three sites installed in 1983, the AgriMet system has now grown to almost 90 sites in Idaho, Oregon, Washington, Montana, Wyoming, and California. Reclamation has cultivated partnerships with over 25 federal, state, and private interests to help fund the operation of the network.

AgriMet stations collect the weather data required for modeling crop ET and transmit this information via satellite to Reclamation's Regional Office in Boise, Idaho. Every day during the growing season, crop water use charts are developed for crops grown in the vicinity of each AgriMet station. This information is available daily through the Internet and is also published in many local newspapers throughout the region. The information is used by federal and state agencies, conservation districts, irrigation districts, extension agents, agricultural consultants, corporate farms, and individual irrigators for water management purposes. The weather data collected is also used for a wide variety of other applications. A rigorous field calibration and maintenance program, and data quality assurance program ensures a high-level of data quality and integrity.

Competition for limited water resources is increasing, cost of irrigation water and pumping is rising, and concerns for surface and ground water quality are heightening. In response to these factors, scientific irrigation scheduling is becoming more commonplace. AgriMet is providing the information required to meet these challenges in the Pacific Northwest.

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Memo

To: Dave Merritt, URS
From: Kara Sobieski
Date: 10/28/2014
Re: Upper Basin Agricultural Study – Meeting Notes from CoAgMet Site Visit

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Wilson Water Group set up a site visit to the climate station on October 24, 2014, in which we met Wendy Ryan from the Colorado Climate Center. The following notes summarize the topics discussed during this site visit.

- Wendy Ryan is the CoAgMet Program Coordinator. The CoAgMet network of climate stations is supported through the Colorado Climate Center (CCC), overseen by Colorado State Climatologist, Nolan Doesken. Wendy's responsibilities include assisting with new station siting and on-site maintenance. She also is responsible for routine calibration efforts.

Climate Station Siting and Existing Stations

- The CoAgMet website includes an indicator of irrigation status (full/partial/dryland) at each site location. Photos of each site are not available on-line at this time while the site is being rebuilt; however, Wendy sent us photos of each.
- There are over 80 CoAgMet stations located throughout Colorado; 18 are located in the Colorado River Basin, mainly clustered in areas of significant irrigation at lower elevations.
- CoAgMet stations are located at CSU Extension facilities throughout Colorado; however, these stations are located essentially in parking lots and there has been resistance to moving them to a more agricultural site.
- One of the stations near Cedaredge is located below orchard canopy and will likely be moved. The Mancos station is fully irrigated and considered a very good station. Towoac got hit by lightning and the modem is fried -- trying to figure out if BIA or CoAgMet will pay to replace it. The Dove Creek station is on dryland.
- FEMA approached CCC to develop an inventory of all CoAgMet stations in Colorado, determine where gaps may exist, and itemize locations for new stations to develop a more complete weather network (i.e., MesoNet). CCC developed the proposal and submitted it to FEMA; may get approved in the next month.
- O&M funding for CoAgMet stations is always in question; however, there is a push to include the funding in the CWCB Construction Bill.

New Climate Stations and Partnerships Currently Contemplated

- Paradox is funded by Reclamation (Andy Nichols) and was planned as a temporary station – it is possible it could be moved to a more agricultural setting.

- AgriMet will likely be taking over the QA/QC of data, but data will still be collected by and served up on the CoAgMet website. CoAgMet will likely be serving up Northern Colorado Water Conservancy District's climate stations' data as well.
- There is a grant proposal with CWI to fund QA/QC of CoAgMet data; may funnel that funding towards AgriMet if they take over the QA/QC of the data.
- Three new stations will be installed in the Gunnison Basin, currently planned near Cimarron, Montrose, and another Uncompahgre site. A phone call with Perry Cabot may be beneficial to discuss the final locations for these stations.
- A new CoAgMet station is approximately $6,000, including sensors, battery, and tele-com instruments but excluding fencing/enclosure.
- CCC recently received funding to install a new style of lysimeter in the North Platte developed by Decagon Devices, Inc. (http://www.decagon.com/) that is less expensive and does not require as much on-sight maintenance/oversight as traditional weighing lysimeters. The plan is to install two that would measure actual ET (be supplied the same as the surrounding cropland) for the first two years and then may switch one lysimeter to measure a full supply (potential ET) after that. She indicated it would be easy to expand the installation to four so starting in year one both potential and actual ET could be measured. If these new devices are effective and measure accurately, they will consider implementation in other basins.
- Regional Climate Reference Networks (RCRNs) were originally located in CO, AZ, NM, UT (and Alabama), and are now being decommissioned and 'gifted' to the States. They have expensive temperature and precipitation sensors, and could be retrofit to include remaining sensors for approximately $2,000 per station. As they have concrete foundations, they cannot be moved. CCC opted to take over all the stations in Colorado; the State Climatologists in other States opted to 'cherry-pick' which stations to keep. WWG needs to contact other States to see which they opted to keep; Wendy will provide a map of RCRN stations in Colorado. No information remains on the NOAA website for this network.

Climate Station Maintenance

- CCC could use more feedback on bad data from climate stations so they can stay on top of maintenance issues; HPCC doesn't provide this report until months later.
- Annual maintenance is approximately $2,000 a year for each station, including a re-calibration of the pyranometer and temperature probe every two years (performed by Campbell Scientific). Wendy performs maintenance on all stations outside of the Arkansas and Rio Grande basins; they contract with a person in the Arkansas for the Arkansas and Rio Grande Basin maintenance. Additional stations may require another contract maintenance person.
- Stations do not require access to a hard line for power; they can run off solar and battery.

- Stations can transmit data using cell coverage (a Verizon plan has reduced monthly rates of $5-$10 per month for computer <-> computer data transfer), radio systems (need a line of sight and potentially a repeater station), a hard phone line (expensive monthly costs), or newly available Wi-Fi options.

Requested information received after the meeting from Wendy Ryan:

- Pictures of all CoAgMet stations.
- Proposal for FEMA inventory projects.
- Map of RCRN stations in Colorado (and any other states available).

Upper Colorado Basin Agricultural Water Consumptive Use Study – Phase II

Updates on Climate Station & Eddy Covariance Tower Placement

TELECONFERENCE MEETING:
November 17, 2014

PARTICIPANTS:
Don Ostler (UCRC)
Kib Jacobson (USBR)
Jim Prairie (USBR)
David Eckhardt (USBR)
Steve Wolf (Wyoming)
Brenna Mefford (Wyoming)
Kevin Flanigan (New Mexico)
Mike Sullivan (Colorado)
Robert King (Utah)
Kara Sobieski (Wilson Water)
Erin Wilson (Wilson Water)
Greg Gates (CH2MHill)
Dr. Richard Cuenca (HEI)
Dr. Chad Higgins (HEI)
Joseph Machala (URS)
David Merritt (URS)

INTRODUCTION:
Group conference call addressing the updates to:
1. Existing climate station locations and methodology used to site future locations.
2. Eddy Covariance Tower placement

Climate Station Location Methodology:
Erin Wilson – Reviewed approaches used by AgriMet (associated with the Bureau of Reclamation) and CoAgMet.
- Costs are consistent ($6K-$8K for each station with an associated O&M cost of approximately $2K a year.
- Current locations of stations are based on landowners' request to have a station on their property.
- These stations come with land access agreements.
  - Usually written up to have a 30-day maximum notice before access but this has never been the case as access can be done with a phone call notification followed by immediate access.
- CO, NM, and UT are all looking at AgriMet to take overall responsibility of their stations.
  - AgriMet performs an internal QA/QC process so data is available for process upon delivery (the QA/QC is included in the $2K O&M costs).

URS

  - CoAgMet does not perform QA/QC of data so quality checks would need to be performed by the recipient before processing.
- Also looked into utilizing current NOAA stations by adding required equipment for the analysis.
  - AgriMet had already looked into this and stated that it is not worth the effort plus there is an impediment concerning data access. It would be less work to just build a new station if there is a current NOAA station in a needed location.
    - Most stations are airport stations as well, and not suited for the analysis (which requires being near irrigated agriculture).
- Stations that are located in increasing development can be moved later to better locations.

<u>Climate Station Location Procedure Steps:</u>

1. Assess sustainability of current station locations in each state.
   a. Talk to users if they are good stations to use.
   b. Ask users if we can move existing stations to better locations.
2. Determine how much acreage is covered by each station.
   a. Consider topographic range and temperature ranges.
3. Collaborate with AgriMet on new station location planning.
   a. Can we encourage where they go?
4. Develop a wish list of best possible locations, prioritize locations, and fit to budget. Then correlate to a location with the Eddy Covariance Tower location. Overall, station location is really based on professional judgment. The time frame for siting potential station locations is early next year (January to February).

Jim Prairie – We could use gridded climate data to use as a comparison with stations.

David Eckhardt – The gridded data is physically based, spatially and topographically correlated, and takes into account cloud cover.

New Mexico would like to look at putting stations on tribal land so the Bureau of Reclamation wouldn't have to pay for them.

Schedule an early December meeting to discuss expanding network and talk about collaboration about new climate stations with Jama, who is located in Boise, ID.

<u>Eddy Covariance Towers:</u>
Dr. Chad Higgins – Looking around Silt, CO for possible locations.

Two sites are promising north and south of Silt.

- The southern site is preferred as it has more irrigated acreage coverage and also experiences water shortage stress at the tail end of the season. There is also flexibility in the location because the southern area is so large. It also seems to be in the mid-elevation range.
- The northern site has less topographic influence and the irrigated lands have ample water supply from nearby reservoirs so no shortages later in the season (better for measurements).

Major variables considered in the tower location include topography, acreage, plant stress from water shortage, and land ownership.

Dr. Cuenca – Satellites pass over the area usually around 10 to 11 a.m. when there isn't a maximum ET for the area, so placing the tower in a water stressed area would help to counteract this to get better readings for actual ET.

Dr. Higgins – Do we need to be worried about MicroMET stations not performing as well in stressed areas?

Dr. Cuenca – Not a real big problem, we will still get valid results.

Dr. Cuenca – Spoke with Chris Neale with the University of Nebraska and Jim Verdin with USGS. Their methodology is summarized in the emailed memo dated 10/24/2014.

- Based on a Bowen Ration comparison/but we prefer Eddy Covariance.
- His report will be done in January of 2015.
- He is testing a lot of our approaches.
- Interested in Eddy Covariance Tower data to verify his data and collaborating on data processing.
- Asked to implement RESET.
  - Would need to have temperature data pre-processed to use.
  - Will also give the reference ET and relative humidity.
  - We will give the data after QA/QC so we are comparing apples to apples.

Dave Merritt – Do we want to operate the station longer than planned to gather data for a full growing season to September 2015? *Unanimous agreement.*

Don Ostler – Are we doing pilot testing in three states because we won't have an Eddy Covariance Tower in the other states?

- We will only have an Eddy Covariance Tower in Colorado but will still have the networks in other states to do the pilot testing.

Ostler – We will wait to present this information for another time other than the upcoming Las Vegan meeting because there are a lot of other topics scheduled. Probably address it next spring.

- The next meeting will be scheduled in mid to late January.
- There will also be updates on the location of the Eddy Covariance Tower.

Upper Colorado Basin Agricultural Water Consumptive Use Study – Phase II

Conference Call: 24 Oct. 2014

Participants: Richard Cuenca, Hydrologic Engineering, Inc.
Jim Prairie, BuRec
Gabriel Senay, USGS
Jim Verdin, USGS

Background

Gabriel Senay and Jim Verdin are working on development and application of the Simplified Surface Energy Balance – operational (SSEBop) model for determination of actual ET using Landsat data. Part of the motivation for this work comes from the recommendation of the USGS to develop a *National Water Census* (USGS, 2007). This eventually led to a congressional mandate under the passage of the SECURE (Science and Engineering to Comprehensively Understand and Responsibly Enhance) Water Act (SECURE Water Act, 2009). This led to approval of the U.S. Department of the Interior's WaterSMART (Sustain and Manage America's Resources for Tomorrow) Initiative (U.S. Department of the Interior, 2010). Three locations were chosen by DOI as the first "focus areas" for the WaterSMART Program: a) the Delaware River Basin (Del., N.J., N.Y., Pa.), b) the Apalachicola–Chattahoochee–Flint River Basins (Ala., Ga., Fla.), and c) the Colorado River Basin (Ariz., Calif., Colo., Nev., N. Mex., Utah, Wyo.). Senay and Verdin are therefore very interested in our goals of investigating operational characteristics of remote sensing procedures for ET in the Upper Colorado Basin.

It had previously been indicated that Senay and Verdin may be able to process Landsat data for the four test sites to be used in the Upper Basin study using SSEBop. This would allow us to determine the characteristics, advantages and disadvantages of an additional data processing method. The objective of this call was to verify if this was possible and to learn what the requirements were for USGS participation.

Topics

1. *What is the interest of USGS in processing Landsat scenes through the 2015 growing season using SSEBop in each of the Upper Basin states, i.e. Colorado, New Mexico, Utah and Wyoming?*

Based on the Colorado basin being one of the first three focus areas in the WaterSMART Program, Senay and Verdin were quite interested in participating in the data analysis for each state, and comparison with eddy covariance data at one site. Final approval would have to come from Eric Evenson and Bret Bruce, both of USGS, who are responsible for the National Water Census and Colorado River Basin Focus-Area Study, respectively. Jim Prairie has previously discussed the Phase II objectives with these individuals and Senay and/Verdin were going to meet with them quite soon and all indications at this time are positive for the participation of USGS. Given that possibility, Senay and Verdin had specific requirements for project participation, as indicated below.

2. *What are the data input requirements of USGS to execute SSEBop over each of the Landsat scenes*

In order that the results of SSEBop be comparable to other Landsat data analysis methods, USGS requires that Landsat surface temperature, T_s, data for each pixel for each Landsat scene be produced. The concept is that all methods, i.e. R-METRIC, ReSET, ALEXI/DisALEXI and SSEBop, would use the same Landsat surface temperature data. Cuenca indicated that HEI would deliver T_s data to USGS in a timely manner. Additionally, given the requirement of reference ET values for interpolating between dates of Landsat scenes and over the growing season, USGS wants the daily reference ET (calculated using the Penman-Monteith equation for a grass reference surface) values associated with each Landsat scene, i.e. based on the nearest micro-met station, so that all methods are using the same value. Cuenca indicated that HEI would deliver ET_o data to USGS in a timely manner. Finally, masking of the target irrigated area for each state is to be done uniformly for all methods tested.

3. *When is it expected that data analysis results for the 2015 growing season are anticipated, i.e. what is the timeline to report out results?*

It was explained that the data for reporting out project results are under discussion. It was anticipated that there may be two project reporting periods for Phase II. The first around the end of June to cover the micromet station and eddy covariance tower placement recommendations (i.e. Task 2) and another towards the end of September to cover Landsat data analysis for ET for the 2015 growing season (i.e. Task 3), realizing that such an extension would require some additional resources. It was emphasized that this plan was under discussion.

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Eddy Covariance Tower Siting
Field Meeting Notes
21 November 2014

On Friday, 21 November 2014, David Merrit, URS, met with Dan Harrison, board member of the West Divide Water Conservancy District, and Jerry Fazzi, the owner of the parcel identified by Dr. Chad Higgins. Dan and David walked the field, and David took a number of photos (see below). The land is gently sloping, situated at approximately 6,400 feet in elevation, is irrigated from the Porter Ditch, and usually runs out of water in July. It is used primarily for pasture grazing, and has excellent access from the County Road.

As David was introduced to Jerry by Dan, the meeting was quite cordial. David indicated what the team's interest was, and that we would only be there for one season. Jerry stated that it would definitely need some panels around it to keep the cows from incessantly rubbing against it. He is willing to have the equipment situated on the land – we just need to keep In touch with him as the project goes forward.

Jerry's contact information is:

Jerry Fazzi
11231 County Road 231
Silt, CO 81652
(970) 379 6004

Memo

To: Dave Merritt, URS
From: Erin Wilson
Date: 2/3/2015
Re: Upper Basin Agricultural Study – Meeting Notes

Jama Hamel organized a meeting to discuss continued and future collaboration between AgriMet and the individual Upper Basin State climate networks. The meeting was held at the Colorado State University Atmospheric Research Center in Ft. Collins on January 23, 2015, and was attended by following:

- Jama Hamel – AgriMet Program Coordinator
- Nolan Doesken – Colorado State Climatologist
- Wendy Ryan – Assistant Colorado State Climatologist, CoAgMet Program Coordinator
- David Dubois – New Mexico State Climatologist
- Jobie Carlisle – Utah State Climatologist
- Patrick Erger – Supervisory Hydrologist, Reclamation Great Plains Region
- Tim Grove – AgriMet Program Coordinator - Montana
- Steve Wolff – Wyoming State Engineer's Office
- Brenna Mefford – Wyoming State Engineer's Office
- Jim Prairie – Reclamation Upper Basin Region
- Rick Allen – University of Idaho
- Justin Huntington – Desert Research Center
- Don Ostler – Upper Colorado Compact Commission Administrator

1) The meeting began with Jim Prairie and Erin Wilson providing an overview of the Upper Basin Agricultural Study to help everyone understand why we were attending and our interest in Upper Basin climate network coordination.

2) Jama then kicked off the discussion with an overview of the AgriMet program and her specific responsibilities, previously limited to Reclamation's Pacific Northwest Region. She has begun operating and maintaining stations in Nevada (Mid Pacific Region), and Jobie Carlisle and Jama have contracted for AgriMet to add additional stations in the Colorado River Basin side of Utah in her climate network. This prompted Jama to begin reaching out to other states in the Upper Colorado Region to see if there were more opportunities for collaboration, and was her primary reason for setting up the Fort Collins meeting.

3) Jama showed the updated map of AgriMet stations, which includes seven new stations in the Colorado River Basin in Utah – some were installed in the fall with others scheduled for installation in March of this year. She highlighted the benefits of working with the AgriMet network including their standards for equipment maintenance and calibration; standards for siting locations only in appropriate agricultural settings; and the data quality control processes that are carried out daily.

   Tim Grove noted that the process used in Montana for their AgriMet equipment maintenance and calibration was the same as the process Jama uses in the Pacific Northwest Region. He used the same data quality control process on a daily basis.

4) Each State Climatologist or State Representative then presented information about their State's networks, including number of sites, types of equipment and condition, staffing, maintenance procedures and schedule, data review, and funding. They each provided views of how a more collaborative process would benefit their State. For example, New Mexico does not have a very wide-spread network; they have only one station in the San Juan Basin. Their maintenance and data quality control procedures are limited by funding. Colorado's network uses the same standard for equipment maintenance and calibration; however, they provide the data as-is and do not perform the data quality control procedures to the level of the AgriMet network. Likewise, Wyoming has similar standards for equipment but relies on the High Plains Climate Center Automated Weather Data Network to perform quality control of the data and make the data publically available.

5) Justin Huntington developed the NLDAS (North America Land Data Assimilation System) 5-kilometer extended climate gridded dataset that was reviewed in Phase I as a potential option for moving forward. He presented the procedure used to develop the dataset and answered specific questions. The dataset relies on minimum temperature, maximum temperature, and precipitation for available stations in any network throughout North America, plus satellite and radar precipitation information, and information that can be derived from land-use mapping. Once the gridded algorithm estimates temperature and precipitation, the grids with climate data are re-calibrated to assure they are weighted more heavily with the actual measured data. Standard equations are used to estimate the other extended parameters including humidity, solar radiation, and wind speed. The goal is to eventually utilize a more robust extended climate system to use actual measured data in lieu of calculated parameters.

6) Rick Allen discussed progress and upgrades made to the METRIC method for estimating evapotranspiration via remote sensing. He provided examples of METRIC estimates compared to lysimeter measurements. His discussion focused on current, early efforts to develop an automated procedure to estimate evapotranspiration between satellite passes and when images have significant cloud cover. This process is in the early stage; but his presentation showed promise.

Erin had maps for each State with existing climate stations and the "wish-list" of proposed new station locations. The plan was to spend a few minutes with each State representative to:

1) determine if there were current plans for more stations and, if so, where they may be sited;
2) get feedback on the general locations proposed for the Upper Basin Agricultural Study; and
3) determine if each State representative would be willing to work with the URS Team to find suitable sites and assist with finding willing local land owners.

The meeting went beyond the six hours designated and had to end on-time because of travel plans; therefore, individual discussions and review of the maps did not occur. However, each of the State representatives indicated their willingness to review the locations and have these discussions over the next few weeks.

2/10/2015
Assessing Agricultural Consumptive Use in the Upper Colorado River Basin
PHASE II: Climate Station Locations and Progress Update
CONFERENCE CALL

Attendees:
Don Ostler (UCRC)
Kib Jacobson (USBR)
Jim Prairie (USBR)
David Eckhardt (USBR)
Steve Wolf (Wyoming)
Brenna Mefford (Wyoming)
Kevin Flanigan (New Mexico)
Robert King (Utah)
Kara Sobieski (Wilson Water)
Erin Wilson (Wilson Water)
Greg Gates (CH2MHill)
Dr. Richard Cuenca (HEI)
Dr. Chad Higgins (HEI)
Joseph Machala (URS)
David Merritt (URS)

TASK II: EDDY COVARIANCE TOWER & STATION LOCATIONS

Update on the project schedule: Hoping to get the Eddy Covariance Tower up and running in March.
- Working on a modification with the contract to operate through December 31st.

AgriMet follows the best practices for calibration and quality checks. Other Colorado providers do not do their own QA/QC.
- This solves the long term problems with us doing the QA/QC.
- We can rely on each State network for the locations but AgriMet can do the calibration and quality checks.

All State Climatologists will help find local owners to build these additional MET stations.

Wilson Water Recommendations for Station Locations (refer to memo emailed out on 2/6/2015)
Approximately 10 stations were removed from the original existing stations list because they did not meet our screening criteria based on field visits.

There is already a lot of action for new climate station sites and we have had some say on their location:
- Eight sites in Utah (AgriMet).
- Six sites in Colorado (for four of these, we provided input for the location).

There are good correlations between sites for minimum/maximum temperatures (refer to Figure 1 in the memo from 2/6/2015).

- Correlation coefficients greater than 0.9 show that one station could represent a greater area (e.g., Hayden could represent the area extending to Maybell).

Table 1 from the memo list State stations that exist or are already planned to be installed (and shows the estimated acreage coverage for each station).

- Farmington could potentially be substituted for all Navajo stations if we cannot get access.
- Approximately 57 percent of the Upper Basin irrigated area is covered by the researched stations that exist or are already planned to be installed.

Table 2 from the memo shows the proposed climate stations from decreasing order from most covered irrigated acreage to smallest area covered.

- The bottom-listed six stations (23 total considering all proposed stations) do not seem to be critical to have which leaves at least 17 additional proposed stations needed for the project.
- Including proposed station location with existing and planned stations, approximately 15 percent of the Upper Basin irrigated acreage is still not covered.
    - This residual area is considered not economically feasible with sporadic locations and low acreage.
- This is quite a bit less than the preliminary 29 proposed climate site locations because there have been new stations added since the preliminary analysis.

Land access agreement for the placement of stations and land owners is pretty simple.

- Fortunately, people more often than not, want a climate station on their land.
- Jama (from AgriMet) stated that AgriMet trains the land owners on simple maintenance issues.
- Talking points should be prepared for the States to talk to land owners regarding why we are proposing to put stations on their land.

We need to develop annual maintenance costs.

- These costs will be finalized with other issues to be added by Jama (AgriMet) in the near future.

We need to discuss holes in funding, and where we can pick up funding to keep certain stations with budget shortfalls from going off-line.

New Mexico – Interested in seeing written description of QA/QC procedures for these stations.

- Follows ASCE standards (does explain hourly data).
- Erin will forward the original attachment and will also add supplemental procedures from Jama (AgriMet).
    - One procedure for equipment and one procedure for the data.

New Mexico would also like to look at the smaller agricultural sites (which really depend on the availability of the Navajo sites).

Eddy Covariance Tower Locations and Preliminary Results (Dr. Cuenca)

Both remote sensing and Eddy Covariance Towers are expected to be up and running for six months (i.e., April 1st to September 30th).

- The objective for the tower is to have one point of ground truth to calibrate the remote sensing results against.
- Christopher Neal (University of Nebraska) would like to use our Eddy Covariance Tower data as a check against his data.
- The team is working with people in Wyoming to look for scenes that represent the agricultural practices as a whole the best.
- These preliminary results are just to show proof of method and show the system running.
- Looking at the end of February to see preliminary ET example results as gut checks for the areas chosen in each State (suggested areas previously emailed out).
    - Wyoming – Recommends using a different site that isn't alfalfa which is atypical for the state.
    - Utah – Liked Dr. Cuenca's area for first-time preliminary results.
    - Colorado – Currently not present on call but will be briefed later to see if area is acceptable.
    - New Mexico – Would like to move the area to the northwest, closer to the San Juans.

Getting the most recent irrigated acreage shapefiles for each State to Dr. Cuenca would greatly aide in the preliminary calculations.

The remote sensing effort is using metric, which is programmed in MatLab.
- Albedo is calculated differently form Rick Allen's approach but is considered the best approach. All other programming is essentially the same.

SSEB (Simplified Energy Balance) – Their program would like to work with us with the scenes for each state and would use their methodology to calculate alternative results to compare to our approach.

Jim Prairie – There are issues with JPL, questions of the validity of Rick Allen's table results, and questions whether the work was done truly blind.
- Hopefully these issues are cleared up and will aide in Dr. Cuenca's procedures.

Is it reasonable to get all stations by this spring?
- Depends on landowners.
- Work with AgriMet to install these stations?
    - Need to check with Jama on taking over the station installations.
    - She installs them herself but is too busy to do all of them but she may be able to purchase them (which may be easier from a contracting perspective).
    - She is available to collaborate on the operations of the stations, but will need help to maintain them for the States.
    - There may be different types of equipment that Jama is comfortable using.
    - Jama was comfortable with the New Mexico and Colorado stations.
    - States to aide in finding right land owners for station locations within the next 30 days.

Erin Wilson will have her work wrapped up by the end of March.
- Would like to have comments in by the end of February to finalize work.
- Will reach out to Don Ostler, Jim Prairie, and Mike Sullivan on progress for those who could not make the conference call or who came in late.

- Review provided by Jama regarding QA/QC of data. Contact her for information regarding more detail for hourly data, if necessary. Send out existing and additional information to the entire team (John Longworth question).
- Update memo to discuss the correlation (1:1 correspondence between stations) as the indicator of representation, and make it clear that the R^2 value only describes how “often” there may not be a great correspondence (Dave Eckhart comment).
- Double check with Jama and Dave Dubois to determine if Jama would be able to take on AgriMet sites (maintenance and calibration) in New Mexico and if that would be acceptable to Dave.
- Talk with Wendy Ryan (CoAgMet) to better understand the difference in standard equipment between AgriMet and CoAgMet and find out if she would be willing to take care of maintenance and calibration if AgriMet equipment was installed in Colorado.
- Work with Dave to develop talking points for landowner discussions.
- Check with Jama on whether she is willing to have others (e.g., Ag Study Tech Team) tag along when she is installing new Utah stations. If so, send the information out to the Tech Team on potential dates/sites.
- Begin working with State Climatologists on identifying potential land owners and when/if they are willing to make contact.

NEXT COFERENCE CALL

The next meeting will tentatively be at the end of April. Dave will send out a Doodle Poll for final date.

The Commission will be having a meeting on May 8th (Denver) to discuss drought conditions; may be able to bring up topics there.

Draft Memo

To:	Dave Merritt, URS
From:	Erin Wilson and Kara Sobieski
Date:	2/6/2015
Re:	Upper Basin Agricultural Study – Recommendations for Extend Climate Station Siting

Introduction

The following general procedure was followed to recommend the use of existing Extended Climate Stations and to propose new Extended Climate Station locations for use in estimating crop consumptive use to support the Consumptive Uses and Losses reporting. This procedure was recommended and approved by the Upper Basin Agricultural Study technical advisory team.

1) Assess the suitability of existing Extended Stations in each State.
2) Identify additional Extended Stations planned by each State and AgriMet.
3) Identify the acreage that could reasonably be covered by existing and planned Extended Stations by reviewing topography and temperature variation as determined from other climate stations (e.g., NOAA). Identify the remaining acreage that is not covered by existing or planned Extended Stations.
4) Focusing on areas with significant irrigated acreage not covered by existing sites, identify the "wish list" of locations for new sites.
5) Prioritize new site locations based on acreage that could be reasonably covered by a new station.
6) Coordinate locations to coincide with Eddy Covariance Tower locations.

Approach and Results

1) Existing Extended Stations (stations that measure parameters required for Penman calculations to estimate potential evapotranspiration) locations were identified in each State during Phase I of the Upper Basin Agricultural Study. The Phase I effort did not include reviewing each station to identify its suitability for long-term use in estimating crop use. In this phase, the climate network administrators in each State were contacted to determine the following:
   - Are the stations located in agricultural settings?
   - Are there routine instrumentation maintenance and calibration procedures in place that meet the standards set forth by the Reclamation AgriMet network?
   - Do the network administrators perform appropriate quality control and quality assurance checks of the collected data using ASCE Standards?

   There were several sites identified in Colorado and Utah that were not located in an agricultural setting or did not meet the site-distance criteria for location. For example, one site in Colorado was located under an orchard canopy; while one site was located in the parking lot of an agricultural research center. In Utah, several sites were high desert sites not intended for agricultural uses.

A network of stations in Utah managed by the Emery County Conservancy District were identified as under-funded and potentially not properly maintained. In addition, the NRCS SCAN stations are generally located at airports to help with real-time weather information. The Utah State Climatologist added new AgriMet stations that generally cover the same region; therefore, the Emery County and NRCS SCAN stations are not necessary for the Upper Basin Agricultural Project. In New Mexico and Colorado, measured data is currently published as-is, and it is the user's responsibility to perform quality control and correction procedures prior to using the data for analyses. Wyoming relies on the High Plains Climate Center Automated Weather Data Network to perform data quality control and corrections, manage the raw and corrected data, and make the data available to the public.

As noted in previous phone and meeting notes, the administrator of Reclamation's AgriMet climate network in the Pacific Northwest Region (Jama Hamel) is working with Utah, Colorado, and New Mexico to potentially collect their network data on a daily basis, perform the quality control and correction, and serve the "corrected" data through the AgriMet website. Raw data would still be available through the states' network websites, and they would still be responsible for equipment maintenance and calibration.

2) Since the publication of the Phase I report, the Utah State Climatologist has worked closely with Jama Hamel to install AgriMet sites in the Colorado River Basin in Utah. Several of these sites were located to replace the underfunded Emery County Conservancy District sites; while others were located in areas without Extended Station coverage. Each of the seven new sites is located in agricultural settings. In addition, Utah worked with AgriMet to identify two additional locations; one on agricultural land served from the Paria River; and one on agricultural land in Castle Valley near Moab.

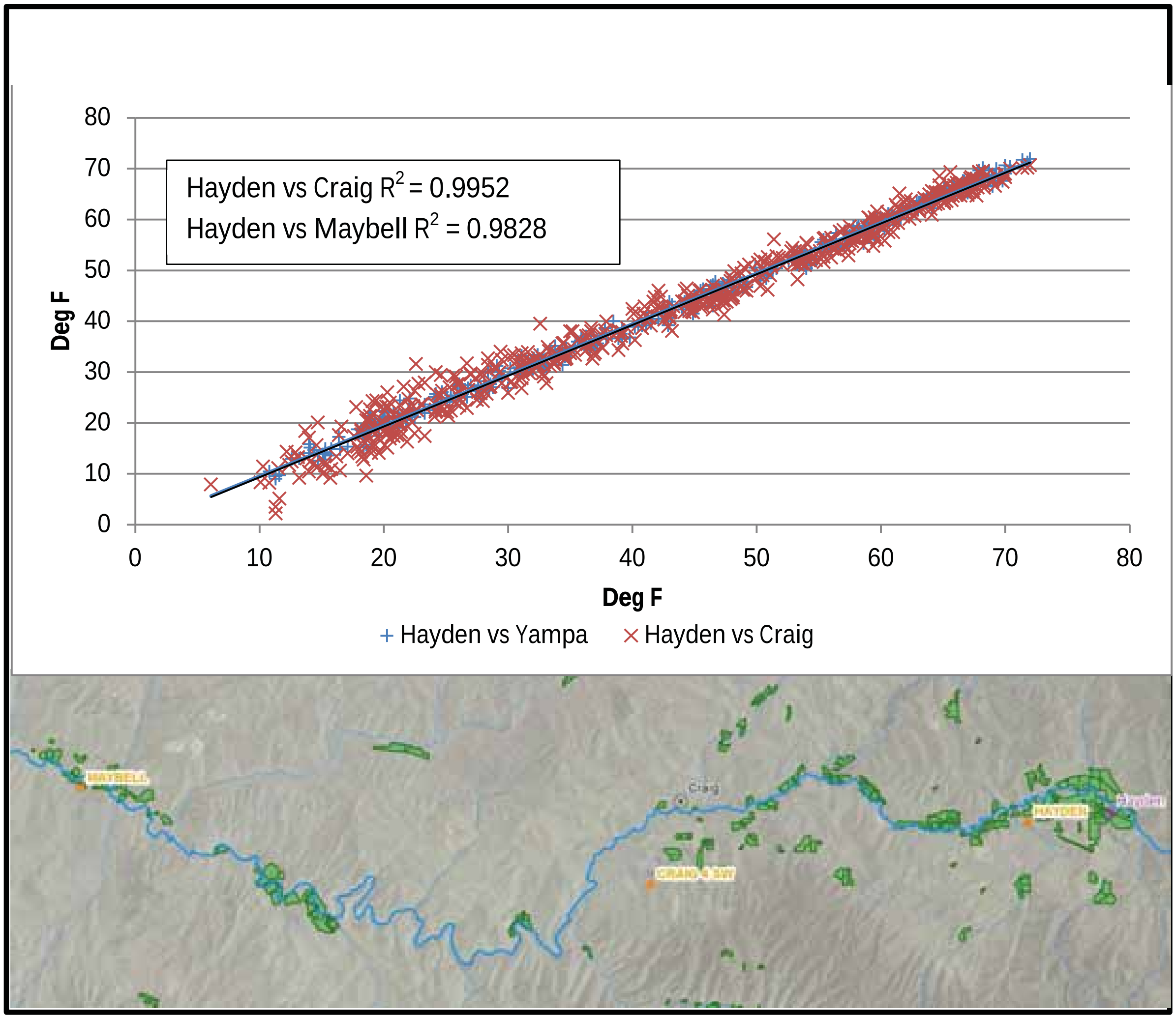
   The Colorado Agricultural Meteorological Network (CoAgMet) has also identified and secured funding to install several new sites in the Gunnison and Colorado River basins in Colorado. Four of those locations are planned for the Gunnison Basin; plus one station that was not in an ideal agricultural setting is planned for relocation to a nearby ranch. Several of the Gunnison Basin stations are to monitor use for a specific project and, although the cost of the equipment and installation has been secured, they may not have long-term funding. Two new stations have been funded for mainstem Colorado River tributaries: one in the Roaring Fork Valley, and one on Silt Mesa.

   The New Mexico State Climatologist indicates there are three Extended Stations on lands irrigated by the Navajo Indian Irrigation Project (NIIP). At this point, the exact locations have not been identified and the equipment maintenance and calibration, and data quality control are unknown. Both the URS team and the State Climatologist have reached out for additional information that will supplement this memorandum when available.

3) The amount of irrigated acreage for which climate could be represented by existing stations and stations already planned for installation was estimated based on reviewing topography, published

average monthly temperature isohyetal maps, and temperature variation as determined from other climate stations (e.g., NOAA). Figure 1 shows an example correlation between mean monthly temperature at the Hayden NOAA station in the Yampa Basin and downstream NOAA stations at Maybell and Craig. The r^2 values are greater than 0.98, indicating that the Extended Station at Hayden can be used to represent acreage near Craig and Maybell. For daily minimum and maximum temperatures, a correlation r^2 value of greater than 0.90 was considered acceptable. This process was used where NOAA (or other temperature/precipitation) stations exist to assist in determining areas for proposed Extended Stations.

Figure 1 – Example Correlation



4) Table 1 lists the existing (i.e., already installed) and planned (i.e., planned for installation by AgriMet or State agencies) Extended Station and the estimated acreage that can be reasonably represented by each station. Around 57 percent of the irrigated acreage in the Upper Colorado River Basin can be reasonably represented by existing or planned Extended Stations. Figures 2 through 11 show the location of existing and planned Extended Stations and the general outline of acreage that could be represented by each station (in black). Note that where several existing Extended Stations could cover irrigated acreage there is an opportunity to use a weighted combination of stations. Once the list of proposed stations is finalized, the recommendations of stations to acreage assignments will be finalized.

   Also highlighted in Figure 7 (circled in green) is an example of irrigated acreage that may be better represented by an additional climate station, but the small amount of acreage (i.e., 1,700 acres) does not warrant the cost of an additional station. Because there is not a nearby NOAA or other climate station, it is not feasible to verify whether the proposed station near Baggs, WY and the existing station in Hayden are appropriate to estimate evapotranspiration for this station. In the Upper Colorado River Basin, about 15 percent of the irrigated acreage fits into this category. These smaller areas of irrigated acreage that are not within the outline of a climate station can be represented by using weighted climate data at two or more nearby stations.

5) Figure 2 lists proposed stations, prioritized from top to bottom based on the acreage they can represent. The general locations of the proposed stations and the general outline that could be represented by each proposed station (in red) are also shown in Figures 2 through 11. The proposed Extended Stations can reasonably represent an additional 28 percent of the acreage in the Upper Colorado River Basin. About 85 percent of total acreage in the Upper Colorado River Basin can be represented by existing, planned, and proposed Extended Stations.

6) The planned Extended Station for the Silt Mesa may be coupled with the Eddy Covariance Tower planned for that general location. It is important that Extended Stations are located with the additional Eddy Covariance Towers and the sites are determined in the future. It is likely that, with the addition of both the planned and proposed Extended Stations, there will be ideal locations to include Eddy Covariance Towers.

Table 1 – Existing and Planned Extended Climate Stations

Station Name	Climate Network	State	Status	Irrigated Acreage
Boulder	WSEO	WY	Existing	53,000
Bridger Valley	WSEO	WY	Existing	74,000
Budd Ranch	WSEO	WY	Existing	43,000
Farson	WSEO	WY	Existing	21,000
Upper Green (maybe relocate)	WSEO	WY	Existing	39,000
Castle Dale	AgriMet	UT	Existing	5,000
Duchesne	AgriMet	UT	Existing	36,000
Elmo	AgriMet	UT	Existing	15,000
Ferron	AgriMet	UT	Existing	6,000
Huntington	AgriMet	UT	Existing	7,500
Pelican Lake	AgriMet	UT	Existing	26,000
Pleasant Valley	AgriMet	UT	Existing	45,000
Castle Valley near Moab	AgriMet	UT	Planned	1,200
Tropic (Paria River)	AgriMet	UT	Planned	2,100
Farmington	NM Climate Center (NMCC)	NM	Existing	6,600
Navajo Indian Irrigation Project (3 Stations, location/quality not known)	NIIP	NM	Existing	70,000
Cortez	CoAgMet	CO	Existing	9,100
CSU Fruita Expt Station	CoAgMet	CO	Existing	39,200
Delta	CoAgMet	CO	Existing	90,000[1)]
Montrose	CoAgMet	CO	Planned	
Olathe	CoAgMet	CO	Existing	
Olathe 2	CoAgMet	CO	Existing	
Hayden	CoAgMet	CO	Existing	17,700
Mancos	CoAgMet	CO	Existing	10,000
Orchard Mesa	CoAgMet	CO	Existing	10,500
Towaoc	CoAgMet	CO	Existing	7,200
Yellow Jacket	CoAgMet	CO	Existing	50,500
Cimarron	CoAgMet	CO	Planned	10,600
Eckert	CoAgMet	CO	Planned	58,700
Gunnison	CoAgMet	CO	Planned	53,300
Roaring Fork Valley	CoAgMet	CO	Planned	25,000
Silt Mesa	CoAgMet	CO	Planned	45,000
Upper Uncompahgre	CoAgMet	CO	Planned	17,300
Total Acreage Covered by Existing or Planned Extended Stations				**894,500**

1) Climate stations all cover acreage under the Uncompaghre Project.

Table 2 – Proposed Climate Stations

Station Name	Climate Network	State	Irrigated Acreage
Upper Green near Daniel	WSEO	WY	44,000
Los Pinos River	AgriMet/CoAgMet	CO	39,400
Neola Area	AgriMet	UT	35,000
Kremmling	AgriMet/CoAgMet	CO	33,500
Steamboat Springs	AgriMet/CoAgMet	CO	30,000
Vernal	AgriMet	UT	25,000
Collbran	AgriMet/CoAgMet	CO	25,000
San Miguel	AgriMet/CoAgMet	CO	24,400
Marvine Ranch	AgriMet/CoAgMet	CO	22,600
Henry's Fork	AgriMet/WSEO	UT/WY	22,000
Little Snake Valley near Baggs	WSEO	WY	20,000
Animas/Florida River	AgriMet/CoAgMet	CO	19,000
Fraser/Upper Colorado	AgriMet/CoAgMet	CO	15,000
Loa/Bicknell Area	AgriMet	UT	13,500
Green River near La Barge	WSEO	WY	13,000
La Plata River	AgriMet/CoAgMet	CO	12,500
Pagosa Springs	AgriMet/CoAgMet	CO	9,500
Aztec (La Plata/Animas)	AgriMet/NMCC	NM	8,500[1)]
Hammond Conservancy District	AgriMet/NMCC	NM	7,100[2)]
Green River	AgriMet	UT	6,000[3)]
Muddy and Quichapah Creeks	AgriMet	UT	6,000[4)]
Hams Fork near Granger	WSEO	WY	5,500[5)]
Shiprock	AgriMet/NMCC	NM	3,400[6)]
Total Acreage Covered by Proposed Extended Stations			439,900

1) Acreage could be represented by a combination of the existing Farmington and proposed Animas/Florida River Stations.
2) Acreage could be represented by the existing Farmington Station.
3) Acreage could be represented by the planned Castle Valley near Moab Station.
4) Acreage could be represented by the existing Ferron Station.
5) Acreage could be represented by the combination of the existing Upper Green and Bridger Valley Stations.
6) Acreage could be represented by the existing Farmington Station.

Next Steps

Once the proposed Extended Station general locations are reviewed and finalized, each State Climatologist and/or State climate network representative has agreed to assist the project team to complete the following steps:

1) Identify land owners that may be interested in allowing a climate station to be located on their land.
2) Determine final instrumentation and installation costs, which may vary by site based on cellular coverage and other considerations.
3) Finalizing the land access agreement and work with the land owner to select the final site that meets the AgriMet/ASCE criteria.
4) Schedule installation and set expectations with the land owner regarding required access in support of an equipment maintenance schedule.
5) Train the land owner on simple maintenance issues that may be required from time to time, for example adjusting a stuck wind gage (*work with Jama on language here…*).
6) Determine the annual maintenance costs for each new station and develop an agreement for continued funding.
7) Others issues (*work with Jama to complete this list*).

It is also critical to make sure that equipment continues to be maintained and calibrated for existing and planned Extended Stations that were identified for project use. The project team will work with each State's Climatologist and/or State climate network representative to identify which stations have long-term funding and which stations may be at risk of losing funding. The project team will determine if annual maintenance costs for these stations should be included in the agreement for continued funding. In addition, the project team will set up a procedure for the UCRC and Reclamation representatives to be notified in the future if the maintenance funding status changes for any of the Extended Stations identified for project use.

Figure 2 – Wyoming (Upper Green River) Extended Stations and Area Covered

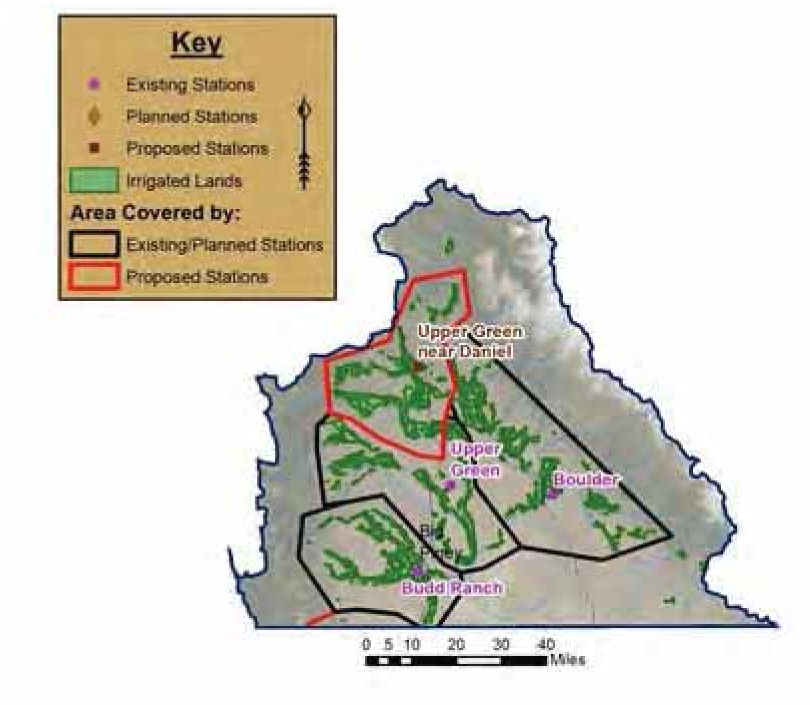


Figure 3 – Wyoming (Lower Green/Little Snake Rivers) Extended Stations and Area Covered

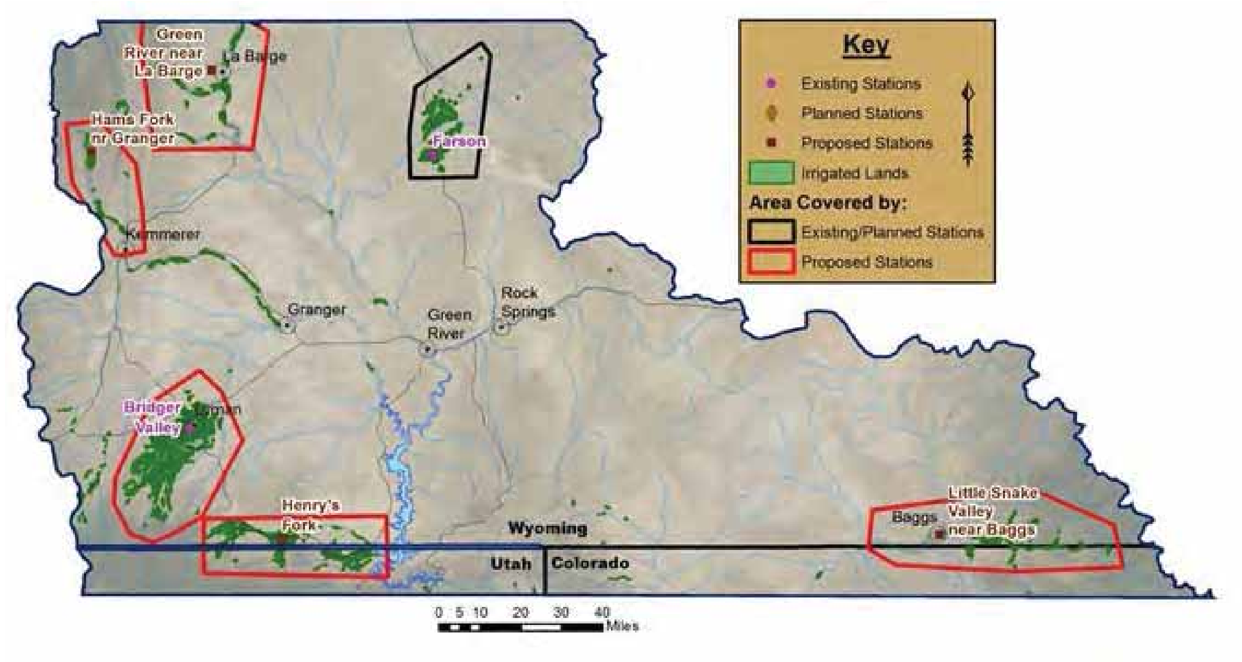


Figure 4 – Utah (Northern Green River Tributaries) Extended Stations and Area Covered

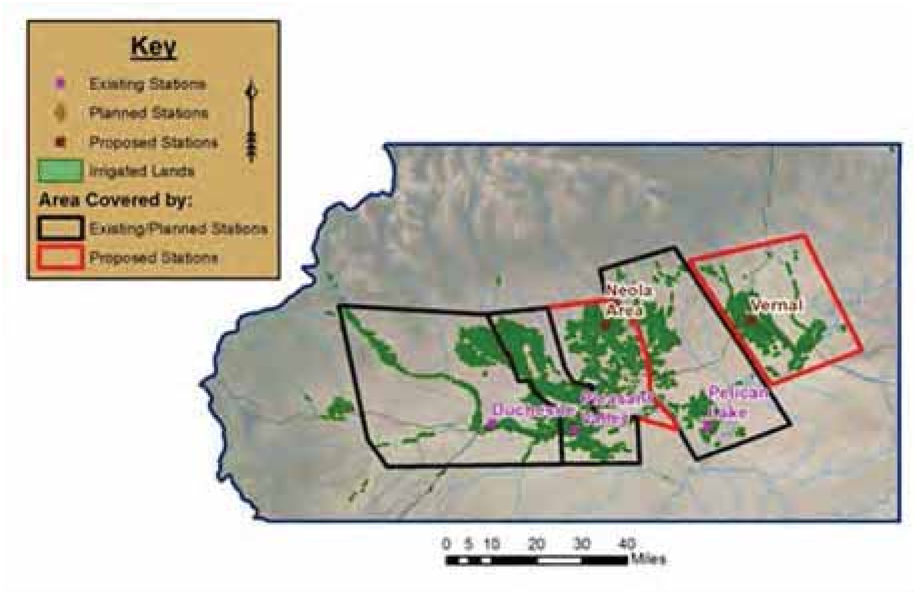


Figure 5 – Utah (Wasatch Range Tributaries) Extended Stations and Area Covered

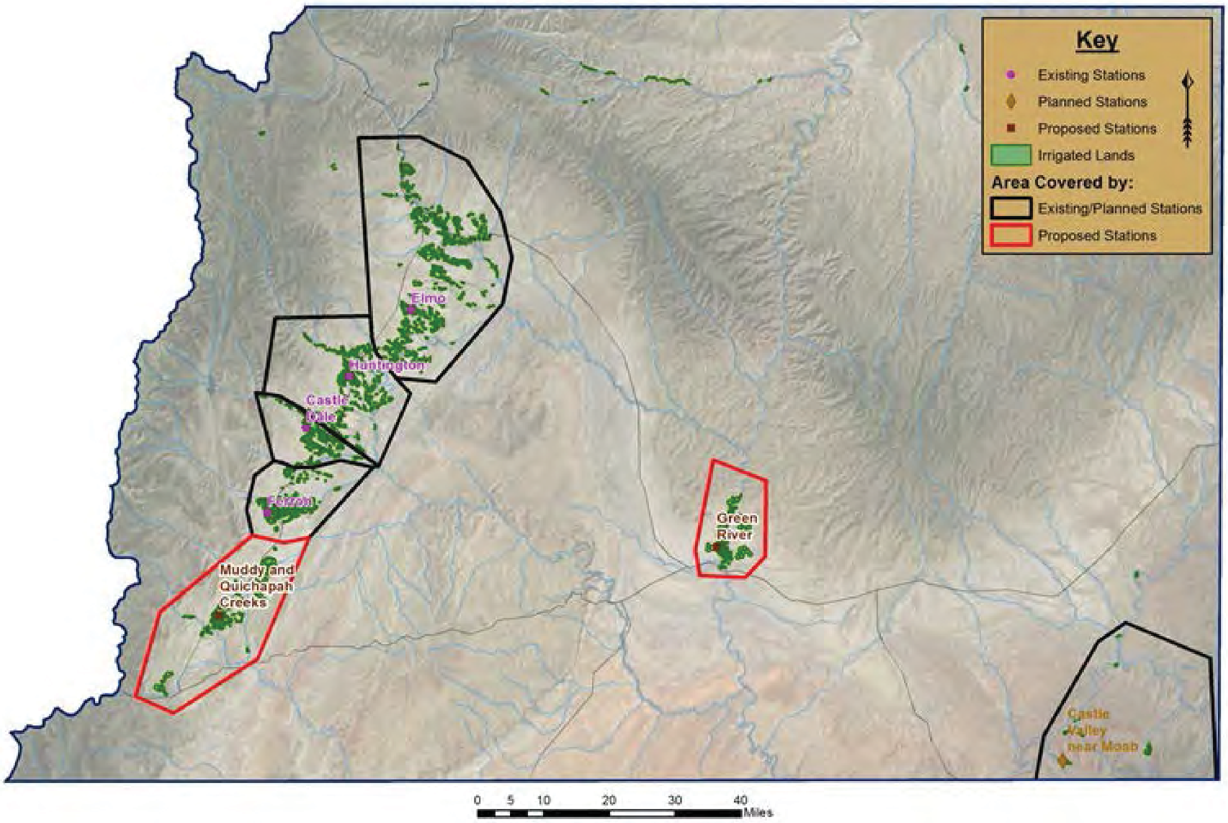


Figure 6 – Utah (Southern Green River Tributaries) Extended Stations and Area Covered

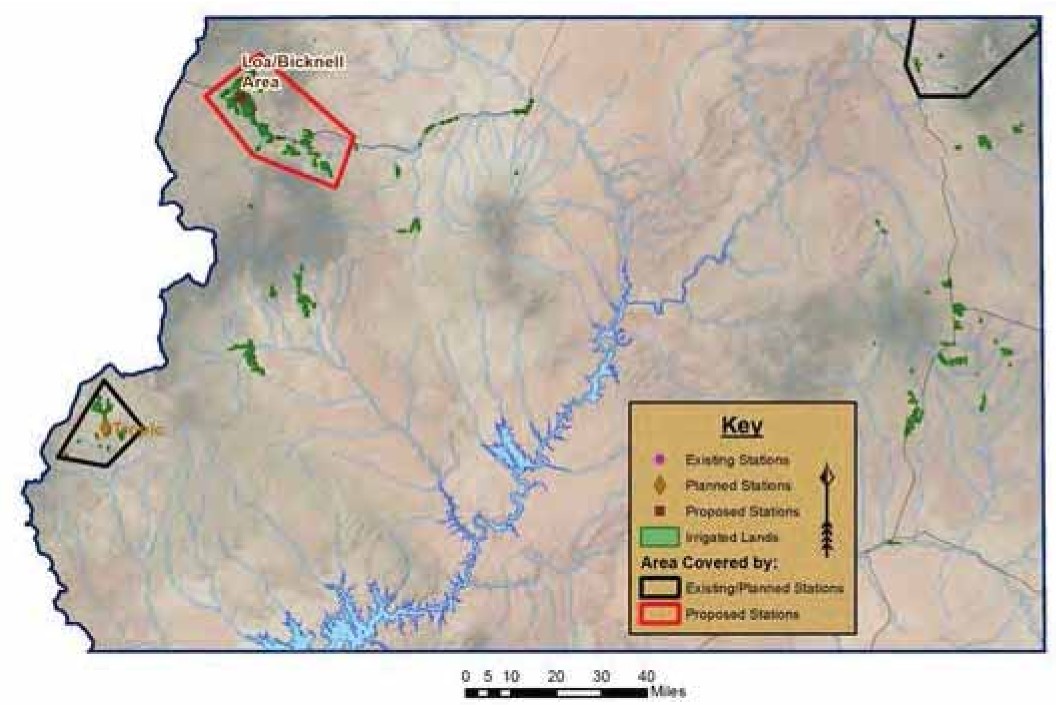


Figure 7 – Colorado (Yampa and White Rivers) Extended Stations and Area Covered

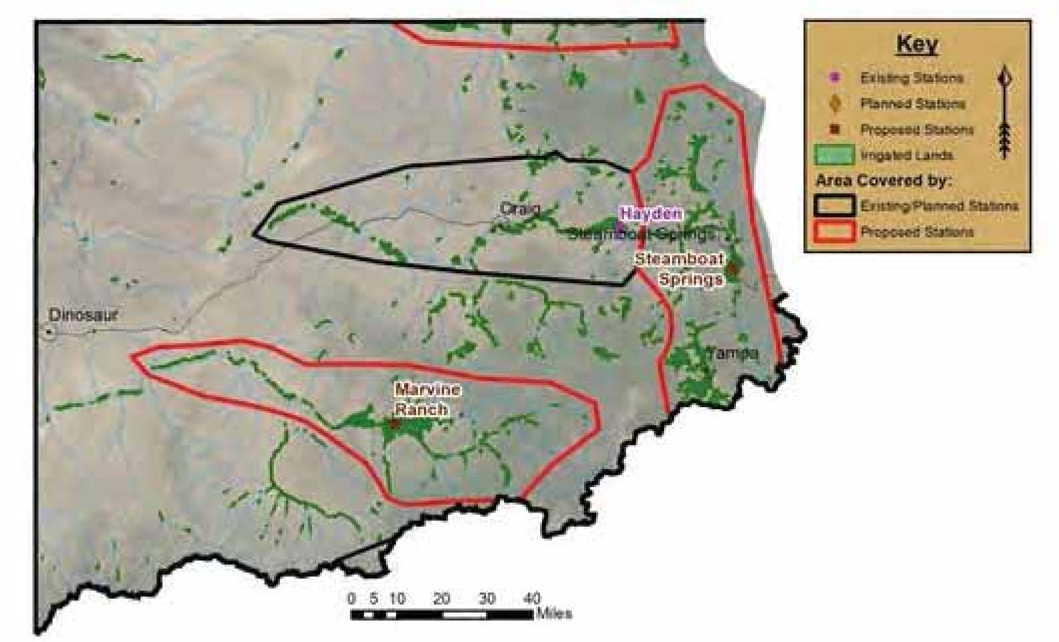


Figure 8 – Colorado (Colorado River) Extended Stations and Area Covered

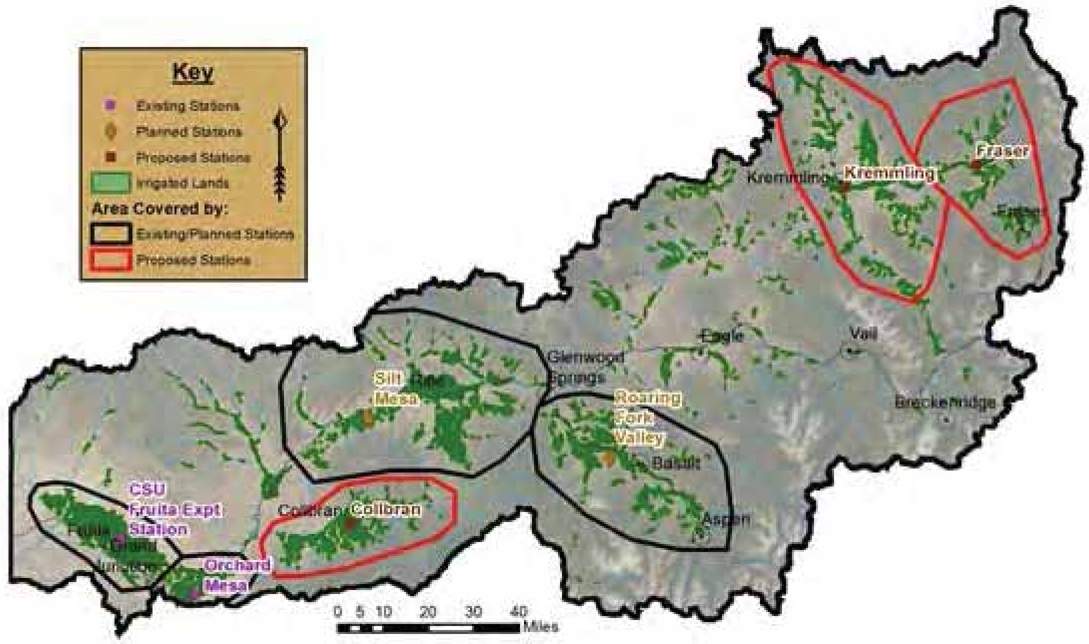


Figure 9 – Colorado (Gunnison River) Extended Stations and Area Covered

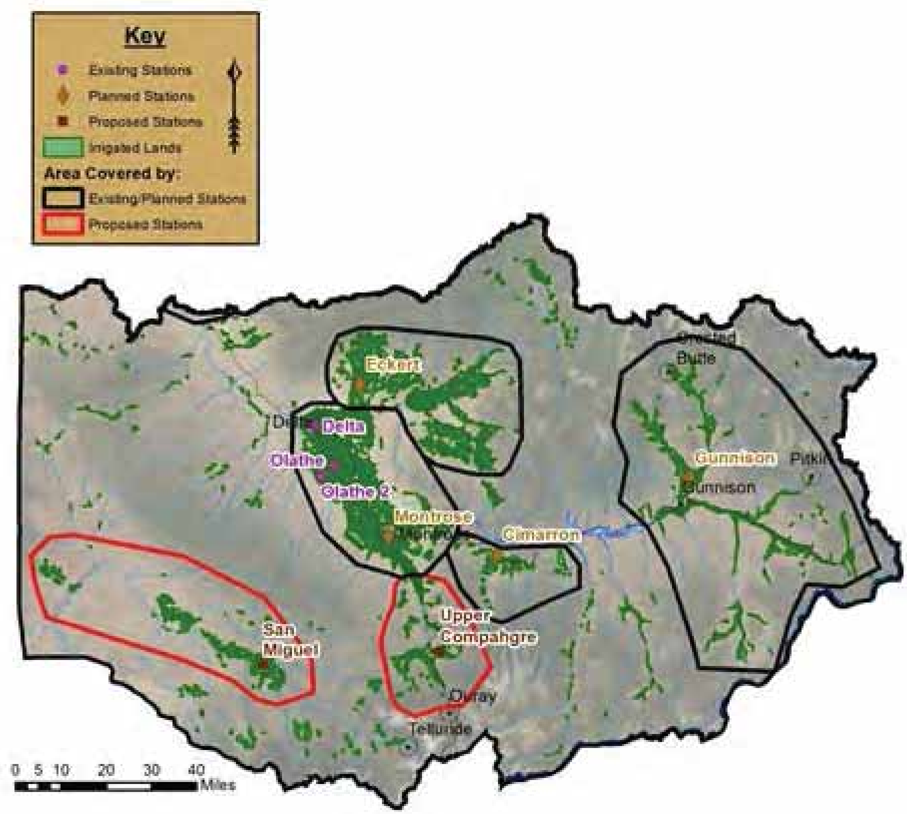


Figure 10 – Colorado (San Juan Tributaries) Extended Stations and Area Covered

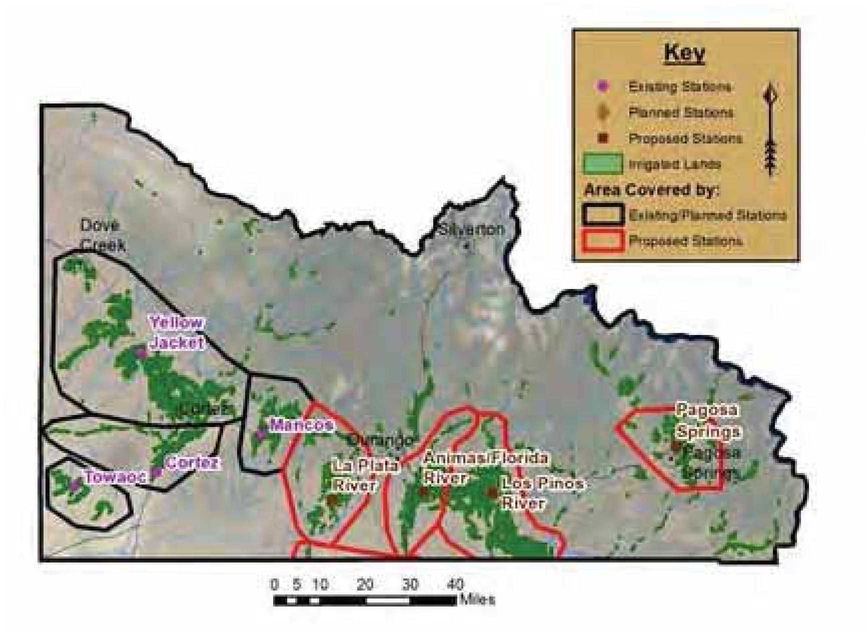
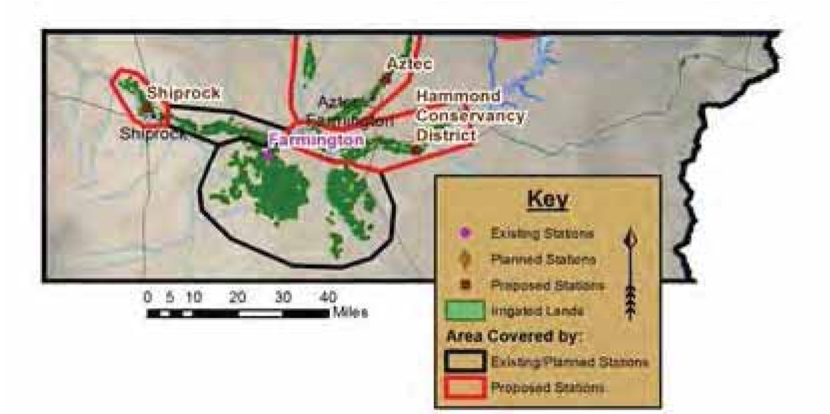


Figure 11 – New Mexico (San Juan River) Extended Stations and Area Covered



5/5/2015
Assessing Agricultural Consumptive Use in the Upper Colorado River Basin
PHASE II: Climate Station Locations, Eddy Covariance Station, and Progress Updates
CONFERENCE CALL

Attendees:
Don Ostler (UCRC)
Kib Jacobson (USBR)
Dr. Jim Prairie (USBR)
David Eckhardt (USBR)
Steve Wolf (Wyoming)
Brenna Mefford (Wyoming)
Kevin Flanigan (New Mexico)
Mike Sullivan (Colorado)
Robert King (Utah)
Kara Sobieski (Wilson Water)
Erin Wilson (Wilson Water)
Greg Gates (CH2MHill)
Dr. Richard Cuenca (HEI)
Dr. Chad Higgins (HEI)
Joseph Machala (URS)
David Merritt (URS)

OVERVIEW
-The contract modification has gone through and the project deadline has been extended to 12/31/2015.
-The tower operation ending date was extended to 9/30/2015.

TASK II: EDDY COVARIANCE TOWER

Chad Higgins:
- The Eddy Covariance station was installed and has been running since 4/1/2015.
- The location was moved approximate 200 meters to the southeast of the original location due to the owner's request to hide the tower from adjacent neighbors.
- Satellite telemetry is operational and used to check on the tower.
- The tower is scheduled to be taken down on 9/30/2015; that is when the owner is planning to release cattle into the field.
- The tower takes 10 measurements every second to have statistically defensible sampling sizes for each hourly report.
- Cell phone service is unreliable in the area and data has to be uploaded via satellite every hour.
- These statistical reports are uploaded every hour and downloaded for QA/QC.
- The tower is approximately 30 feet high.
- The sensors (soil heat flux, humidity, etc.) are located approximately 9 meters high.

- The tower is also set up to do the Bowen Ratio approach to compare apples to apples with Chris Neale's work.
- There was one instance of snow accumulation on 4/13/2015 that covered the solar panel. This shut the tower down for that day and as a result, no data was collected that day.
    - This can also occur during intense rainfall events and strong wind storms, and from spider webs.
- Results from the tower will not be shared with Dr. Cuenca to keep the modeling results blind to the actual data.

Dave Eckhardt:
- Asked and Chad clarified that there may be cuttings during the tower operations but no cattle will be in the area until 9/30/2015.
- It also might also be useful to have some of the tower data to help calibrate the model.

Chad will send out sample daily data patterns (without values to keep the study blind) to the group to show typical data patterns collected by the tower.

TASK II: STATION LOCATIONS

Erin Wilson:
- Erin has information from all states as to what types of instrumentation are used and relayed that information to Jama at AgriMet.
- Jama has reviewed the instrumentation setups and deems them acceptable as they are -- no modifications should need to be done to the existing stations for the project.
- The Navajo sites are pending and waiting to hear about costs.
- The States will continue to maintain their stations.
- A cost estimate of operations/maintenance of the stations as well as QA/QC of the data will be completed within the next couple of weeks.
- Need to have mechanism to fund the project to keep up with all these stations in each state.

Jim Prairie:
- Question about the 2-meter tower heights in Colorado compared to the AgriMet 3-meter tower heights?
    - The 2-meter tower height is an ASE Standard and is acceptable to AgriMet.
    - The ASE has a correction factor to move interchangeably from 2 meters to 3 meters.
    - Crop type for this season will also need to be completed for this study based on field observations.
- Currently there are no direct sites for calibration.
    - There is a site near Boulder, CO that is continuously irrigated to use for calibration and three is also a known site for NM.
    - Currently there is not one known site or Utah but checking with Utah State.
- Current State's data will be used to calculate Penman-Monteith estimates for a comparison for this growing season. The Eddy Covariance Tower is already setup to do that analysis at that location.

Dave Merritt:

- Worked with Don and Kib (Reclamation) to secure funding for the next season cycle for the project.
- No money this year will be put to more stations.

Dr. Cuenca:

- Data will be supplied to the USDA to run their own in-house model for comparison.
- There is a good chance that LANDSAT 9 could be underway due to the need for projects like this and the water resource problems arising in the west.
- Will deliver ET data results of ET after calculation from Proof of Concept document to each State and member of the project team.

The next call is scheduled to be around the middle of June. Dave will send out a Doodle Poll to help nail down a specific date.

6/23/2015
Assessing Agricultural Consumptive Use in the Upper Colorado River Basin
PHASE II: Climate Station Locations and Progress Update
CONFERENCE CALL

Attendees:
David Merritt (URS)
Don Ostler (UCRC)
Kib Jacobson (USBR)
Jim Prairie (USBR)
David Eckhardt (USBR)
Steve Wolf (Wyoming)
Brenna Mefford (Wyoming)
Kevin Flanigan (New Mexico)
Robert King (Utah)
Kara Sobieski (Wilson Water)
Erin Wilson (Wilson Water)
Greg Gates (CH2MHill)
Dr. Richard Cuenca (HEI)
Dr. Chad Higgins (HEI)
Chris Shrimpton (URS)

TASK II: CLIMATE STATION & EDDY COVARIANCE TOWER PLACEMENT

Wilson Water Group - Review of Climate Station Location Discussions
Erin reported that Jim Prairie did a very good job updating the principals at the UCRC meeting in Durango on the project status.

Wyoming is in the process of installing all of the Met Stations on their list. That leaves 13 to 14 additional new stations to be installed, at a cost of about $140,000. Jama has reviewed the equipment currently operating on the stations and is satisfied with the quality of the equipment and the data that are being generated. The Navajo Nation has three stations and is interested in potentially working with AgriMet to coordinate equipment and data QA/QC.

The struggle in Colorado is that they need budget to maintain the existing stations we would like to use for this project. CoAgMet has insufficient money to operate and maintain all of its stations. They did receive some money from the CWCB, but will be looking for more money from the State just to operate and maintain the existing stations, which is expected to be in the range of $1,500/station/year. For their network of existing stations to be useful for this project, we need to assure they are being maintained at the appropriate level. Discussions are ongoing to figure this out.

New Mexico needs additional funding and may ask the AgriMet staff to come in to Farmington and assist with calibration.

URS

CoAgMet staff has given a cost to push data back and forth between the AgriMet system and the CoAgMet system. Colorado is debating whether they will push the raw data to AgriMet or will do the QA/QC themselves.

Dave Dubois is considering having AgriMet do it for New Mexico. Wyoming will be performing QA/QC on their data and providing access to the data through the Water Resources Data System and the University of Wyoming.

Dr. Chad Higgins Update on Eddy Covariance Tower Operations (refer to memo emailed out on 2/23/15)

- Station has operated continuously since April 1st with no problems.
- Site visit to perform routine maintenance and data download occurred on June 5 and 6, 2015.
- High precipitation has led to vigorous pasture growth, now greater than 70 cm.
- Equipment on the tower ran continuously since last site visit with no interruptions.
- All data from April 1 through June 5 have been analyzed and evaporations calculated.
- Presented plots of fluctuations in latent heat flux, carbon dioxide flux, sensible heat flux, and net radiation over the course of a typical day.

Current Activities:

1) Georeferencing the ET measurement footprint: the measurement footprint of the tower is transient and depends on the atmospheric conditions and the wind direction. Footprint must be attributed to a location to make satellite inter-comparison possible.

2) Contextual evaporation estimates: the Pennman-Monteith and Bowen Ratio estimates of evaporation for the site location are underway.

3) Investigation of the impact of QA/QC practices on the final results: e.g., alternative 'spike direction' schemes exist in literature. Their purpose is to detect outliers in the fast response data. Currently trying three such routines to determine importance of this choice. Outcomes will be discussed in summary report.

4) He will be working on a report on the siting and operational needs for these towers for the entire Upper Colorado area. It will most likely require a Masters level individual to operate these towers.

Dr. Richard Cuenca Discussion of Remote Sensing Model Comparisons (refer to memo emailed out on 2/23/15)

- Remote sensing group has had monthly conference calls.
- 27 scenes from LandSat 7 & LandSat 8 from all four states are clear enough to use.
- All clear or almost clear LandSat scenes have been processed through DOY 159 (08 Jun).

URS

- HEI has distributed:
    - selected Landsat scene designations;
    - evaluation as to whether scene was usable, partially usable, or not usable due to cloud cover; and
    - required meteorological data for each state to the remote sensing group at approximately 10-day intervals.
- From available crop shape files and CropScape, HEI will be processing crop water use data for the selected Landsat path/row for each state by crop.
- HEI presented animated video of example output for irrigated areas in the region of Farmington, NM from DOY 097 to 113 indicating the actual ET for each irrigated feature on daily basis.
- Dr. Cuenca is evaluating the computational "horsepower" necessary to go operational on these evaluations, and will have some recommended computer specifications.
- As stated previously, USGS will run the SSEBop procedure, HEI will run R-METRIC and ReSET (with assistance of Dave Eckhardt of BuRec), and USDA will run ALEXI/DisALEXI in-house.

NEXT CONFERENCE CALL
Next meeting will tentatively be at the end of August in Denver. Dave will send out a Doodle Poll for final date.

OTHER ISSUES
- Who will fund O&M? Individual State Engineers Offices must decide.
- Will future stations be mobile or fixed?
- Who will be hired to manage sites? How many? Likely looking for Masters level with some degree of experience in this sort of work, including coding experience.
- Lost power at a site near Farmington and those data are not recoverable. Erin is trying to get some hourly data from Keller-Bleissner that may assist in re-creation of that data.

To: UCRC CU Losses Remote Sensing Study Team
From: Dr. Chad Higgins
Date: 6/19/2015
Re: Informational update on Colorado Tower operations:

A site visit to perform routine maintenance and data download occurred on June 5-6, 2015. Unusually high precipitation this spring has led to vigorous pasture growth, with the vegetation now >70cm. The equipment on the tower ran continuously since the last site visit with no interruptions. All data for the project between the dates of April 1 and June 5 have now been analyzed and evaporations calculated.

Current activities:

1) Geo-referencing the ET measurement footprint: the measurement footprint of the tower is transient and depends on the atmospheric conditions and the wind direction. To make satellite inter-comparison possible, the footprint has to be attributed to a location.
2) Contextual evaporation estimates: the Pennman-Monteith and Bowen Ratio estimates of evaporation for the site location are underway
3) Investigation of the impact of QAQC practices on the final results: e.g. alternative 'spike detection' schemes exist in the literature. Their purpose is to detect outliers in the fast response data. We are currently trying 3 such routines to determine the importance of this choice. Outcomes will be discussed in a summary report.

An 'example day' was chosen to illustrate the types of data we capture, and the typical daily cycle. Axis labels are left off from these plots to keep the satellite comparison blind. We output evaporation (latent heat flux) every 30 minutes. In this way, one can observe the daily cycle of fluxes. Typical behaviors: low fluxes at night, high fluxes during the day, corresponding to the total available energy. High evaporation is associated with downward carbon flux (uptake by the growing pasture). The fluctuations in the flux measurements are also apparent (e.g around the peak evaporation). These fluctuations are typical of turbulence derived measurements.

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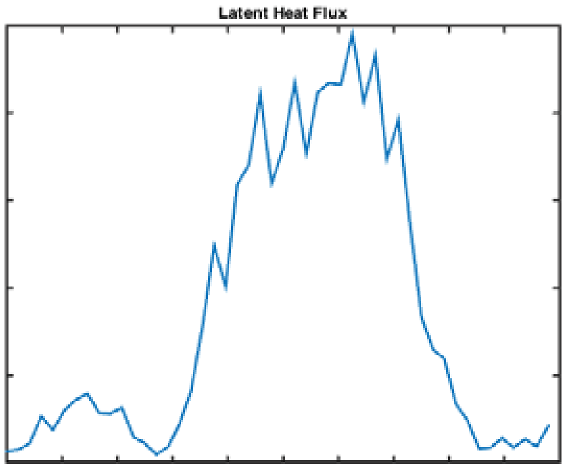

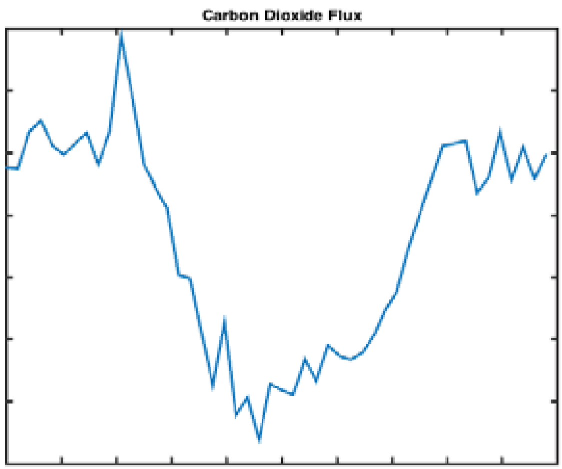

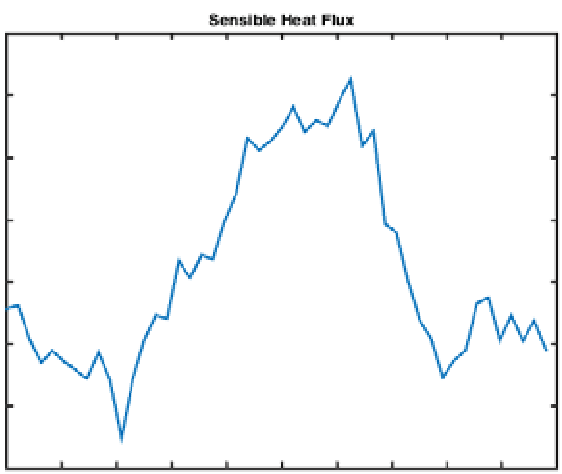

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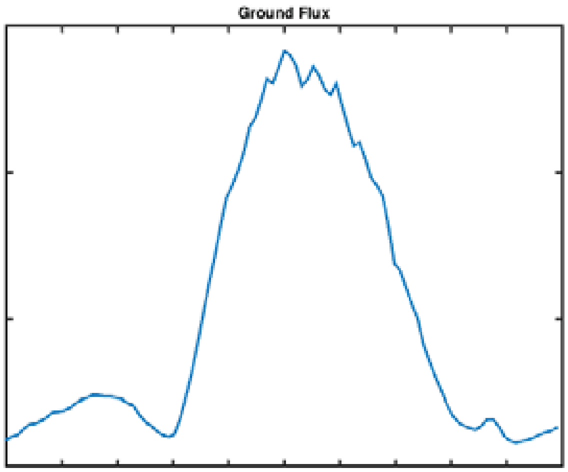

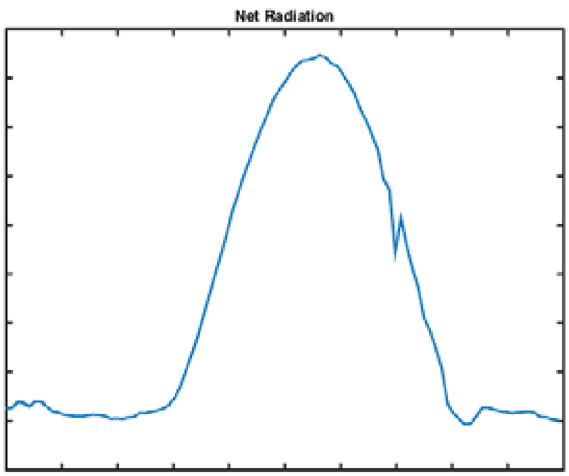

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To: UCRC CU Losses Remote Sensing Study Team
From: Dr. Richard Cuenca
Date: 6/18/2015
Re: Current Status of Remote Sensing Project

As far as HEI is concerned, Theresa Ring and I have processed all clear or almost clear Landsat scenes for all four states through DOY 159 (08 Jun). The remote sensing group has had monthly conference calls. HEI has distributed selected Landsat scene designations, evaluation as to whether the scene was fully usable, partially usable or not usable due to cloud cover, as well as the required meteorological data for each state to the remote sensing group at approximately 10-day intervals. From the crop shape files we have and CropScape, we will be processing the crop water use data for the selected Landsat path/row for each state by crop as shown in the list below:

CO:

Alfalfa
Other Hay/Non Alfalfa
Corn
Dry Beans
Winter Wheat
Sweet corn

NM:

Alfalfa
Corn
Dry Beans
Winter Wheat
Potatoes

UT:

Other Hay/Non Alfalfa
Alfalfa
Corn
Oats
Barley

WY:

Other Hay /Non Alfalfa
Alfalfa

An example of the output we are developing using R-METRIC is the animated video file attached for irrigated areas in the region of Farmington, NM from DOY 097 to 113. The video indicates the actual ET

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for each irrigated feature on a daily basis. Days of Landsat 7 or Landsat 8 overpass with clear or limited cloud conditions were 097, 105 and 113. The days in between were interpolated using the reference ET ratio from the associated meteorological station, i.e. Farmington, which therefore dictates the day to day variation. We have taken the legend off of this graphic since all the teams are to develop their crop water use numbers independently. We still have to do a little work on screening cloud effects in this video. It is fine to distribute this animation file with the agenda for the conference call and it will aid in the discussion. Let me know if you have any questions.

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8/24/2015
Assessing Agricultural Consumptive Use in the Upper Colorado River Basin
PHASE II: Climate Station Locations, Eddy Covariance Station, and Progress Updates
Denver Meeting

Attendees:
Don Ostler (UCRC)
Kib Jacobson (USBR)
Jim Prairie (USBR)
David Eckhardt (USBR)
Steve Wolff (Wyoming)
Brenna Mefford (Wyoming)
John Longworth (New Mexico)
Mike Sullivan (Colorado)
Robert King (by phone) (Utah)
Kara Sobieski (Wilson Water)
Erin Wilson (Wilson Water)
Greg Gates (CH2MHill)
David Merritt (AECOM)

Project Recap
D. Ostler:
- Provided background of the project thus far, noting the project successes including installation and processing of Eddy Covariance Tower data, and identification of climate station network.
- Noted we are waiting on the final remote sensing results.
- Noted the next Commission Meeting on December 2, 2015, and that it would be beneficial to:
  - have one more call before Commissioner meeting,
  - have a draft report ready for their review, and
  - have a list of questions to help the Commissioners make decisions.
- Noted that some project elements/decisions may not be able to wait until the December meeting.

Implementation of New Climate Stations (handout by E. Wilson)
- Review the handout for specific details, only conversation notes reflected herein.
- Climate Station Approach – Recap:
  - Noted that the group agreed on the approach, and that AgriMet is the standard for climate stations within the network.
  - Narrowed the original "wish list" and eliminated several climate stations from the original estimate; able to cover the irrigated lands using fewer climate stations than anticipated.
  - Now that climate stations have been selected/cited, need to coordinate the location of the three Eddy Covariance Towers near existing/proposed climate stations.

- Existing and Planned Stations
  - Wyoming is covering the installation cost and O&M cost for their five new stations; reducing the total climate station network costs.
  - B. Mefford noted the coordinates of the planned Hams Fork near Granger Station was incorrect in the handouts – she will send Erin the new coordinates.
  - Fraser Climate Station in Colorado should have been removed from the map in the handout.
- Proposed Climate Stations
  - Thirteen proposed climate stations, three in Utah and 10 in Colorado.
  - No proposed stations were identified for New Mexico in the handout; however, significant discussion was had over the use of Navajo Block 1 and Navajo Block 9.
    - The group noted concern over the long-term commitment from the Navajo Nation to provide access and support to their climate stations in terms of this project. A formal agreement between Navajo Nation and AgriMet would likely be necessary; consider involvement or cost sharing with BIA.
    - Currently working with Tribal consultant, Keller-Bliesner.
    - J. Longworth noted the climatic differences between the mesa (Farmington station) and the valley along the San Juan and suggested a station in the valley. E. Wilson will follow up.
    - Data from the Navajo Block 1 station was used to shore up data when the Farmington Climate Station went down; Dr. Cuenca's staff was reviewing the similarities of the ET data between the two stations.
- Costs for New Stations
  - AgriMet will not manage the new stations – they are generally located too far for them to visit, and the States already manage other stations in their States.
  - AgriMet will help put together a "Calibration Kit" and will meet with State staff for a few days to walk through calibration and data QA/QC procedures.
    - AgriMet is also willing to share the algorithms and visual graphics used to QA/QC data.
    - Wyoming noted that if AgriMet standards differ from their standards, they will likely not change their procedures/standards.
  - There will need to be an agreement that if any of the stations in this network are to be retired or defunded, they will notify the group.
  - Wyoming noted their data currently all goes through High Plains Climate Center, but it will be moving through the Water Resources Data System (WRDS) soon.
  - Wyoming noted they will not be asking for any funding for O&M of their climate stations.
  - Colorado noted they are currently advertising for at least one new position to assist in maintaining climate stations and managing climate data.
  - Original costs for new stations were estimated to be $300,000 for purchasing and installing stations, with $65,000 for O&M each year.
  - Revised costs of $185,000 for the first year (less 1/5 covered by Reclamation), and $36,000 (less 1/5 covered by Reclamation) for subsequent years, is already set aside in the MOU funds.
  - K. Jacobson noted that MOU funds could be used for subsequent year O&M.

- **Costs for Existing Stations that Will be Relied On, Tech Team Recommendations, Process to Secure Funding**
    - A majority of the acreage lies in Colorado, the bulk of the first year cost will be used for climate stations in their State.
    - Wyoming noted that it has already paid for stations, and that no additional costs should come out of Wyoming MOU funds. The MOU funding however assumed the cost for the purchase and installation of climate stations would be split evenly between the States.
        - D. Ostler noted that even though the climate station wasn't located in one's State, the State would ultimately benefit from the use of more accurate climate data.
        - D. Ostler did not know the process of changing the MOU agreement and funding.
        - Wyoming tentatively agreed to split the cost evenly and looked for other opportunities to recuperate their MOU costs (e.g., Eddy Covariance Tower).
    - The option of splitting the subsequent O&M costs evenly or based on where the climate stations are located was discussed; however, individual States are looking into other funding mechanisms outside the MOU for this long-term funding.
    - The tentative agreement to evenly split the first year costs and pro-rate subsequent O&M costs needs to be finalized by Commissioners.
    - The group noted the importance of documenting why this network is being created and maintained, both for the Commissioners meeting and for future defensibility of the data.
- **Next Steps**
    - Contractual issues associated with Federal/State use of Federal/State owned stations or sensors needs to be investigated by the individual States and Reclamation in September, and wrapped up by the end of September.
    - Meeting/phone call in late September or early October to discuss the feasibility and success of the Remote Sensing effort.
    - See below for additional next steps.
- **Remote Sensing Update**
    - D. Merritt provided an overview of Dr. Cuenca's Remote Sensing summary; see the handout materials for more information.
- **Commission Charge to Consumptive Use Technical Work Group**
    - D. Ostler noted that the general charge of the group by the Commission was to support himself and the UCRC's commitment to the Upper Basin States.
    - The group that the Near-Term timeframe is 3-4 years, the Mid-Term timeframe is 5-8 years, and the Long-Term timeframe is 8-15 years.
    - The group agreed that the decision point for the use of Penman-Monteith (PM) would likely occur after the Near-Term timeframe, and the decision point for the use of Remote Sensing would likely occur after the Mid-Term timeframe. It was noted that these are decision points only and that the use of either of the methods is not set in stone.
- **Near-Term Options, Mid-Term Options, Long-Term Options, and Tech Team Recommendations**
    - The group agreed that the Near-Term option as presented by E. Wilson would likely be a combination of Status Quo "Plus" and State Provided.

- The group began discussing whether Remote Sensing or PM should be used and D. Ostler indicated this discussion was too soon; rather, the group needs to wait for the Remote Sensing results before deciding.
- D. Ostler inquired how we can make the Status Quo better, and the group discussed how UCRC, Reclamation, and the four States should continue to meet and talk about moving forward focusing on finding a way so there is less disputing and more information sharing.
- D. Ostler suggested the name of the Ag Management Group (the group to move forward with the effort) have a more active name such as Consumptive Uses and Losses (CU & L) Steering Committee (note CU & L Steering Committee is used to designate this group in these notes).
- J. Prairie indicated that Reclamation was able to incorporate others' data and that Reclamation is open to other methods and using better information.
- J. Prairie cited examples of how Reclamation's modeling was revised in the past based on a more accurate method of effective precipitation.
- J. Prairie provided examples of how better data could be incorporated into the Reclamation modeling, including irrigated acreage, crop types, water supply information, and calibrated coefficients. He also cited that documentation on how data or information was developed is a must before consideration for incorporation into the Reclamation modeling.
- J. Prairie indicated the importance of maintaining the credibility of the Reclamation modeling, particularly in light of natural flow estimation. He has concerns about a fractured dataset (information for only part of the period) and having enough information/documentation to apply the revisions retroactively.
- Colorado still wants to incorporate diversion records into the process, and the group cited that other States may not or legally be able to obtain that information.
- J. Prairie recommended a tiered Reclamation "standard" modeling method, in which the first tier may be the incorporation of diversion records, and the second tier may be the consideration of other water supply information.
- J. Longworth cited the difference in crop consumptive use and water supply in the early period of the model compared to now.
- E. Wilson reminded the group that both actual and potential consumptive use (to understand shortages) is required for the Compact; D. Ostler agreed and indicated that UCRC needs to know how much the Upper Basin States are using and who (in terms of seniority) is using or not using the water.
- Individual modeling efforts in the States or academic arena are beginning to look at the use of Remote Sensing and/or PM in the Upper Colorado Basin.
- Reclamation will run PM with the 2014 data for comparison purposes in the next couple months, and begin to think about how to "backcast" the results of PM into the natural flow estimations.
- Comparisons between Remote Sensing results, original Reclamation method, and PM results could be made next year; however, J. Prairie noted that outside help (consultants) would be needed to pull all those comparisons together.
- D. Ostler noted that the results of this analysis and others would serve as the discussion topics/materials for the CU & L Steering Committee. Additional topics/comments from the group on the CU & L Steering Committee include:
  - Conduct quarterly meetings,
  - Identify the "right" people to attend,

        - Identify and address the "low-hanging fruit,"
        - Stay with the Reclamation method for now, but find ways to improve it quickly,
        - Review crop coefficients, and
        - Bring in experts as needed.
    - Each State and Reclamation needs to determine what type of information from the comparison they would need to make a decision on PM or Remote Sensing.
    - J. Longworth noted the group should show caution in moving forward with the PM method in Reclamation without Commissioner buy-in and fully understanding the impacts.
- **Process to Secure Funding**
    - The group discussed potential issues with Federal/State sensors and/or replacement parts on Federal/State stations. Wyoming noted this issue is part of the reason they would like to fund the stations themselves.
    - K. Jacobson indicated Reclamation could provide a property transfer of sensors at the outset instead of after depreciation or when they need to be replaced, as Reclamation is covering 1/5 of the subsequent O&M funding.
    - In general, an MOU is needed that discusses the over-arching procedure regarding the payment/receipt/use of Federal and State equipment.
    - The group tentatively agreed to split the first year costs evenly and will continue to discuss internally how each State would like to fund subsequent year O&M costs.
- **Next Steps**
    - The technical consultants and Reclamation need to lay out key decision points for the Near-, Mid-, and Long-Term timeframes so the States can present them to the Commissioners.
        - Install and pay for Met Stations – Capital & O&M – 12/2/2015.
        - Side by Side Penman – start this summer.
        - Decision point – 2 to 3 years.
            - Evaluate Tech-Legal-Policy Issues.
        - Decide on Remote Sensing – after December 2nd meeting.
            - Bigger Pilot Study and more work?
            - Side-by-Side analyses.
            - Full-scale implementation – accept and buy in.
        - Develop process to accept State or USBR data.
    - Lay out the creation of the CU & L Steering Committee.
    - Dr. Cuenca to be in attendance at next meeting to discuss the feasibility of the Remote Sensing results.

Next meeting is scheduled for October 5th in Denver; D. Merritt has sent out the calendar invitation and general agenda.

Agenda
Estimation of Actual Evapotranspiration
August 24, 2015

1. **Implementation of New Climate Stations**
   - Climate Station Approach - Recap
   - Existing and Planned Stations
   - Proposed Stations
   - Costs for New Stations
   - State Costs for Existing Stations Relied On
   - Technical Team Recommendations
   - Process to Secure Funding
   - Next Steps
2. **Remote Sensing Update**
3. **Standardizing Agricultural CU Estimates and Reporting**
   - Commission Charge to Consumptive Use Technical Work Group
   - Near Term Options
   - Mid Term Options
   - Long Term Options
   - Technical Team Recommendations
   - Process to Secure Funding
   - Next Steps

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1) Implementation of New Climate Stations

Climate Station Approach - Recap

- Assess suitability of existing Extended Stations
  - AgriMet Staff reviewed equipment used by Wyoming, Colorado, New Mexico, and Navajo and determined it met Standards
  - AgriMet installed Utah Stations to Standards
- Identify additional Stations planned
- Identify the acreage that could reasonably be covered by existing and planned Stations
  - Consider topography
  - Consider temperature variation as determined from other climate stations (ex. NOAA)
- Identify remaining acreage not covered by existing or planned Stations
- Focusing on areas with significant irrigated acreage not covered by existing sites, identify the "wish list" of locations for new sites
- Prioritize new site locations based on acreage that could be reasonably covered
- Coordinate Eddy Covariance Tower locations to coincide with Extended Stations (3 Stations Proposed)

Existing and Planned Stations

- Colorado installed 5 new stations in 2015 (previously shown as Planned, now shown as Existing) and plans to install 1 additional new station before 2016 irrigation season
- Wyoming plans to install 5 new stations before 2016 irrigation season (shown as Planned)
- Utah plans to install 2 new stations before 2016 irrigation season

Existing and Planned Extended Climate Stations

Station Name	Climate Network	State	Status	Irrigated Acreage
Bridger Valley	WSEO	WY	Existing	74,000
Boulder	WSEO	WY	Existing	53,000
Upper Green near Daniel	WSEO	WY	Planned	44,000
Budd Ranch	WSEO	WY	Existing	43,000
Upper Green (maybe relocate)	WSEO	WY	Existing	39,000
Henry's Fork	WSEO	WY	Planned	22,000
Farson	WSEO	WY	Existing	21,000
Little Snake Valley near Baggs	WSEO	WY	Planned	20,000
Green River near La Barge	WSEO	WY	Planned	13,000
Hams Fork nr Granger	WSEO	WY	Planned	5,500
Pleasant Valley	AgriMet	UT	Existing	45,000
Duchesne	AgriMet	UT	Existing	36,000
Pelican Lake	AgriMet	UT	Existing	26,000
Elmo	AgriMet	UT	Existing	15,000
Huntington	AgriMet	UT	Existing	7,500
Ferron	AgriMet	UT	Existing	6,000
Castle Dale	AgriMet	UT	Existing	5,000
Tropic (Paria River)	AgriMet	UT	Planned	2,100
Castle Valley near Moab	AgriMet	UT	Planned	1,200
Delta	CoAgMet	CO	Existing	90,000 1)
Montrose	CoAgMet	CO	Existing	
Olathe	CoAgMet	CO	Existing	
Olathe 2	CoAgMet	CO	Existing	
Eckert	CoAgMet	CO	Existing	58,700
Gunnison	CoAgMet	CO	Existing	53,300
Yellow Jacket	CoAgMet	CO	Existing	50,500
Silt Mesa	CoAgMet	CO	Existing	45,000
CSU Fruita Expt Station	CoAgMet	CO	Existing	39,200
Roaring Fork Valley	CoAgMet	CO	Existing	25,000
Hayden	CoAgMet	CO	Existing	17,700
Upper Uncompahgre	CoAgMet	CO	Planned	17,300
Orchard Mesa	CoAgMet	CO	Existing	10,500
Mancos	CoAgMet	CO	Existing	10,000
Cortez	CoAgMet	CO	Existing	9,100
Towaoc	CoAgMet	CO	Existing	7,200
Navajo Block 1	NAPI	NM	Existing	45,000
Navajo Block 9	NAPI	NM	Existing	30,300
Farmington	NMCC	NM	Existing	6,600
Total Acreage Covered by Existing or Planned Extended Stations				**993,700**

1) Climate stations cover acreage under the Uncompaghre Project

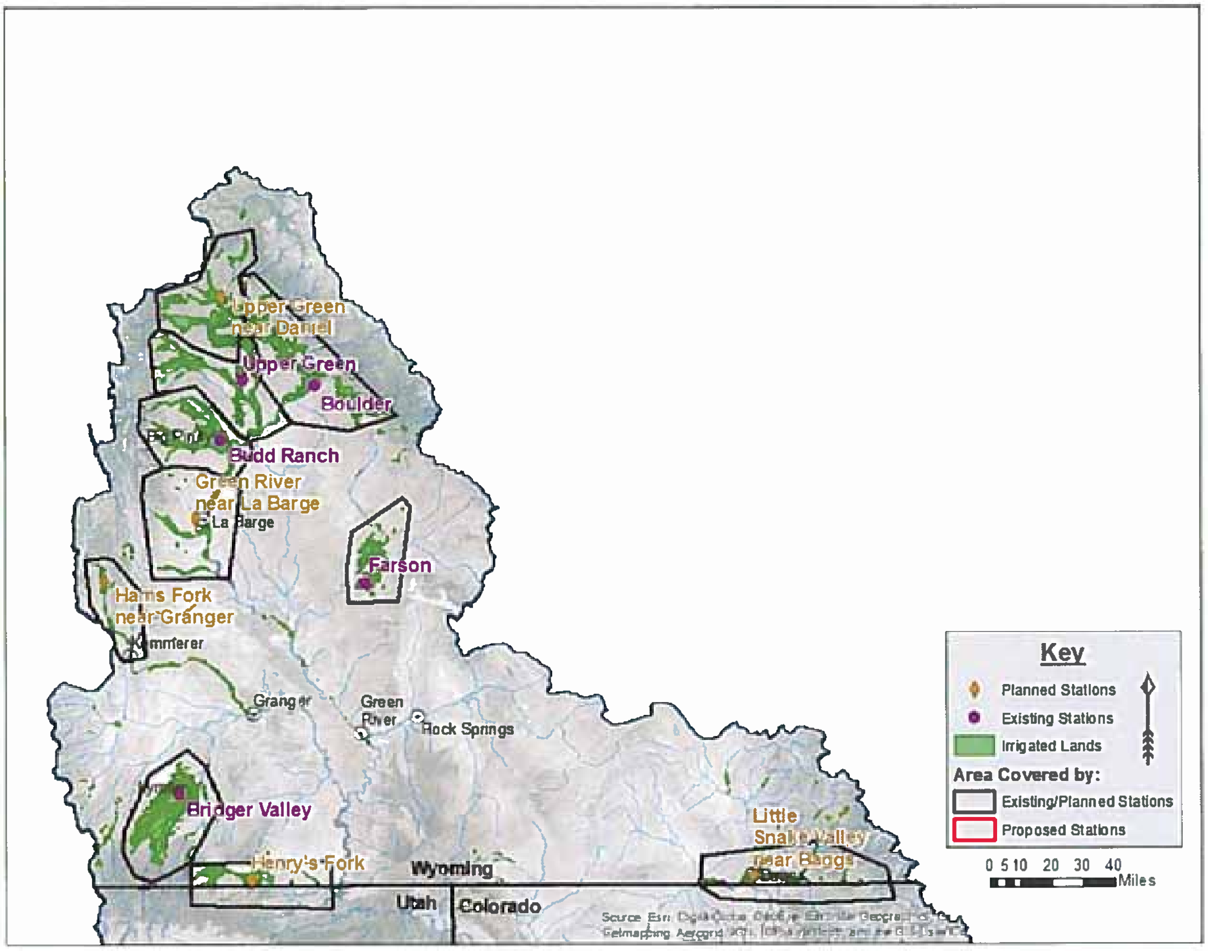
Proposed Stations

Table 2 – Proposed Climate Stations

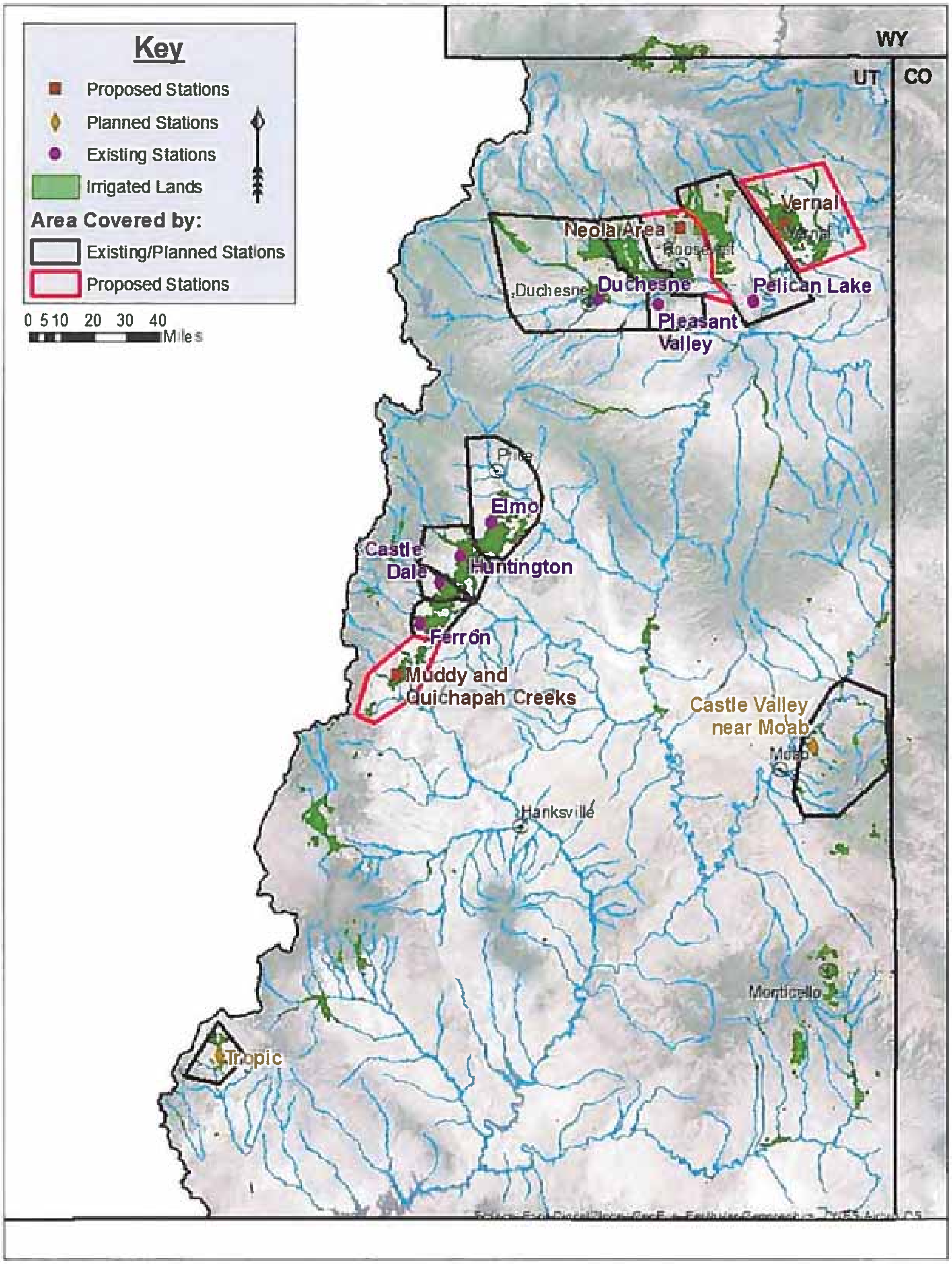
Station Name	Climate Network	State	Irrigated Acreage
Los Pinos River	CoAgMet	CO	39,400
Kremmling	CoAgMet	CO	33,500
Steamboat Springs	CoAgMet	CO	30,000
Collbran	CoAgMet	CO	25,000
San Miguel	CoAgMet	CO	24,400
Marvine Ranch	CoAgMet	CO	22,600
Animas/Florida River	CoAgMet	CO	19,000
Fraser/Upper Colorado	CoAgMet	CO	15,000
La Plata River	CoAgMet	CO	12,500
Pagosa Springs	CoAgMet	CO	9,500
Neola Area	AgriMet	UT	35,000
Vernal	AgriMet	UT	25,000
Loa/Bicknell Area	AgriMet	UT	13,500
Total Acreage Covered by Proposed Extended Stations			**304,400**

- Approximately 85% of Irrigated Acreage Covered by Existing, Planned, or Proposed Stations

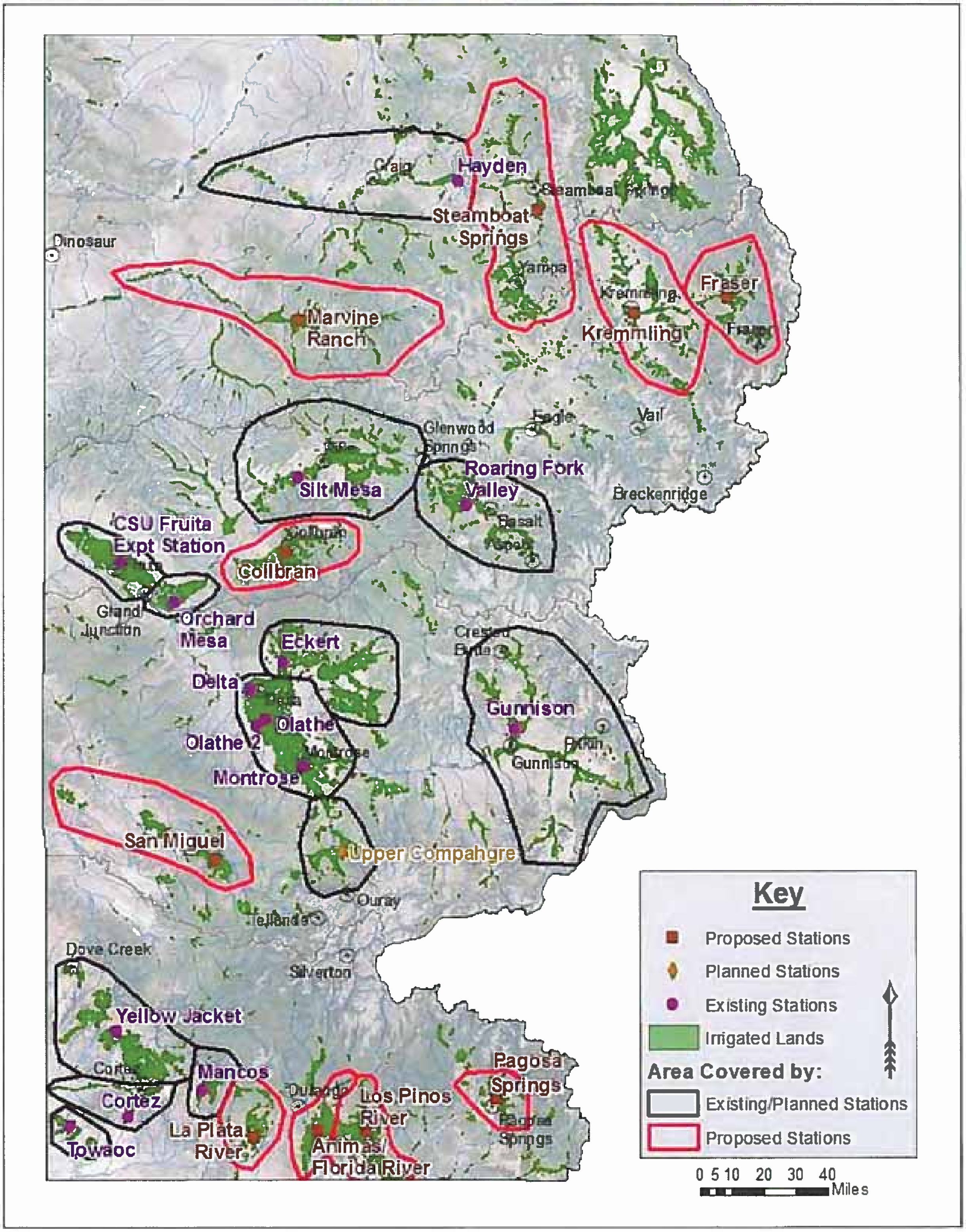
- Areas with less than 9,000 acres not specifically selected can be covered by combination of other Existing or Proposed Stations



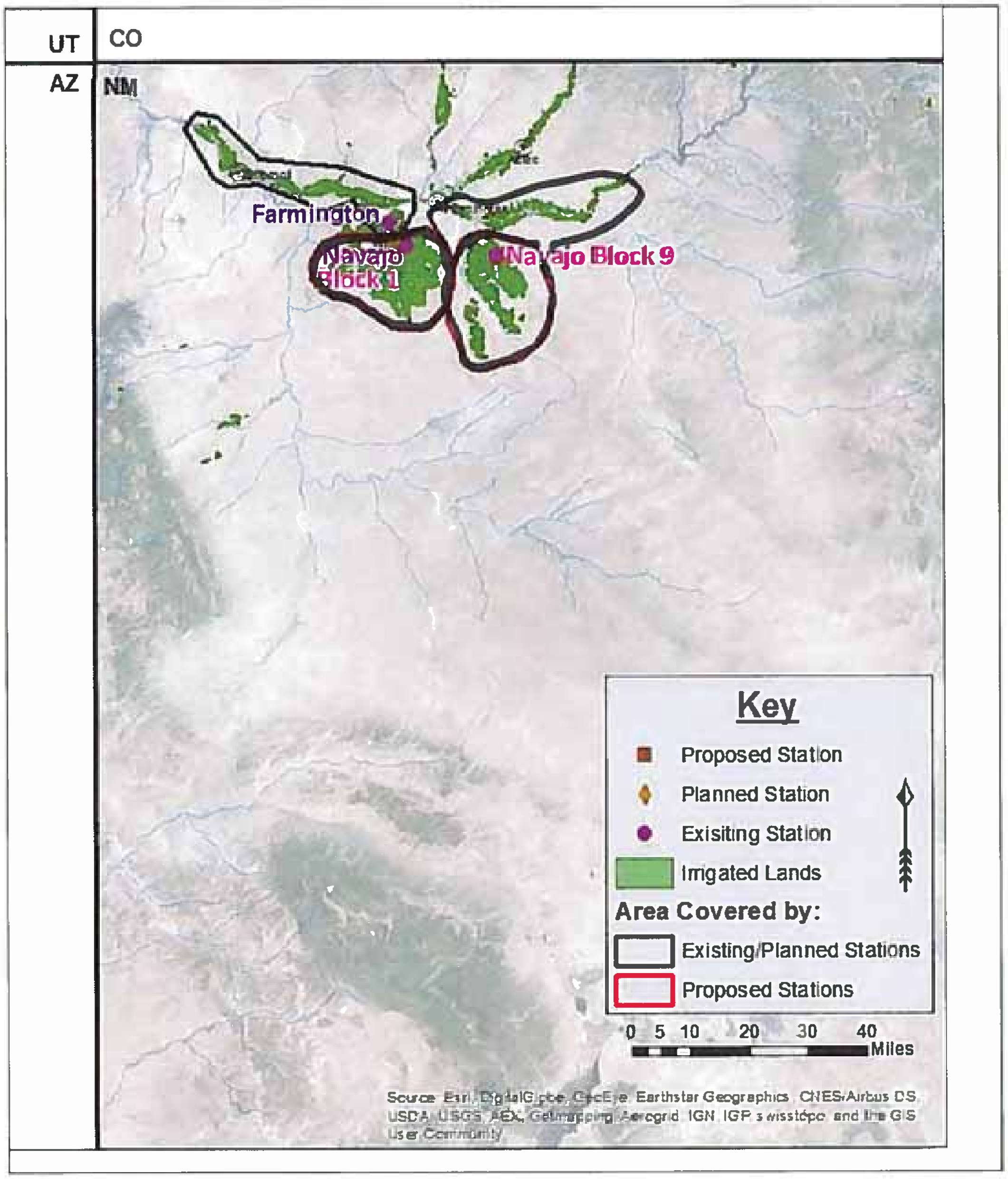
Wyoming Existing and Planned Climate Stations



Utah Existing, Planned, and Proposed Climate Stations



Colorado Existing, Planned, and Proposed Climate Stations



New Mexico Existing Climate Stations

Costs for New Stations

- Wyoming, Colorado, New Mexico, and Navajo are willing to have AgriMet Staff review annual Maintenance and Calibration Procedures. AgriMet already reviews/participates in Utah's program.
- Colorado and Wyoming will QA/QC and provide their data through existing websites. Colorado and Wyoming are willing to work with AgriMet Staff to assist with development and review of data QA/QC Procedures. AgriMet Staff currently QA/QC and provide data through AgriMet's website.
- New Mexico and Navajo are interested in AgriMet performing data QA/QC and providing the data.
- Colorado and Utah State Climatologists are willing to identify land owners that would be good "stewards" of new climate stations.
- Colorado and Utah State network staff will work with land owners to show them how to trouble-shoot common maintenance issues.
- Wyoming is identifying land owners and siting planned climate stations through the State Engineers office.

New Costs for Proposed Climate Stations

Cost Item	Unit Costs	Number Required	One-Time Costs	Annual Costs	Proposed Reclamation Share
Purchase and Install new Climate Station	$9,000	13 [1)]	$117,000	N/A	
Develop Calibration Kits and Review/Assist with Data QA/QC Processes [2)]	$8,000	4	$32,000		
Operation and Maintenance [3)]	$1,750	16 [4)]	N/A	$28,000	
Data QA/QC [5)]	$500	16 [4)]	N/A	$8,000	
First Year Costs	**$185,000**				**$37,000**
Subsequent Year Annual Cost	**$36,000**				**$7,200**

1) Includes 10 new stations in Colorado (installed by CoAgMet network) and 3 new stations in Utah (installed by AgriMet network)
2) AgriMet will assist Wyoming, Colorado, New Mexico, and Navajo with the development of Calibration kits and review Wyoming and Colorado's method for data QA/QC. Assumes that AgriMet will take responsibility for the QA/QC of New Mexico and Navajo data. Costs include $3000 for each kit, and AgriMet staff costs for 1 week in each State to review procedures ($5,000).
3) Operation and Maintenance includes data communication costs; site visits; and sensor cleaning and calibration
4) Includes new stations plus O&M on the New Mexico Farmington station and 2 Navajo stations
5) Data QA/QC Includes meteorological data and metadata management and data quality control for new stations plus New Mexico Farmington and 2 Navajo Stations

- Reclamation would cover 1/5 of the costs associated with the new climate stations separate from the Basin States MOU finds.

Costs for Existing Stations that will be Relied On

Costs Incurred for Existing Stations that will be Relied on for Agricultural Use Estimates

Cost Item	Wyoming	Utah	Colorado	New Mexico
Number of Existing or Planned Stations	10	9 [1)]	16	3 [2)]
Purchase and Install existing Climate Stations (One Time Costs)	$90,000	$81,000	$144,000	$27,000
Operation and Maintenance	$17,500	$15,750	$28,000	$5,250
Data QA/QC	$5,000	$4,500	$8,000	$1,500
Annual Cost	$22,500	$20,250	$36,000	$6,750

1) Possible that some stations were purchased by AgriMet?

2) Includes 2 Navajo Stations

Technical Team Recommendations

- Discussion Item

Process to Secure Funding

- Discussion Item

Next Steps

- Finalize February 6, 2015 Draft Memo "Upper Basin Agricultural Study – Recommendations for Extended Climate Station Siting" to include:
    - Technical Team Recommendations
    - Final Costs
    - Funding Process

2. Remote Sensing Update

Status of Investigation, Costs for Eddy Covariance Towers, etc.

3. Standardizing Agricultural CU Estimates and Reporting

Commission Charge to Consumptive Use Technical Work Group:

1) Continue discussion of a management approach for consumptive use determinations in the Upper Basin that would:
    - Improve coordination and defensibility
    - Increase integrity and independence
    - Address timing and frequency of reporting
    - Encourage common standards and quality control

2) Discuss short term and longer term options that can be considered and work with the Legal Committee of the Commission to formulate and report back with recommendations

For Discussion, can we agree that:

- Near Term is 3 to 4 years?
- Mid Term is 5 to 8 years?
- Long Term is 8 to 15 years?

Options identified by Reclamation and Consultant Team during Nov. 21, 2013 meeting with UCRC Commissioners and Phase I report:

Near Term Options

- Status Quo:
    - Reclamation Estimates Agricultural Consumptive Use using Blaney-Criddle and Indicator Gage Method, States may review but do not officially "accept"
    - States may prepare their own, but do not generally provide to Reclamation (except New Mexico)
    - Potential Issues: More than one estimate of Ag use will exist; not moving toward an approach that meets Commission Objectives; Indicator Gage Method not documented and not defensible
    - Potential Benefits: Path of least resistance, does not require any change

- Status Quo "Plus":
    - Same as Status Quo
    - Install new Extended Climate Stations and adopt maintenance and calibration and data QA/QC procedures
    - Add official Ag Management Group with State and UCRC representatives to establish schedules for review and coordination and provide recommendations/revisions to current Reclamation methodology
    - Potential Issues: States will likely continue to generate other estimates; unclear if there can there be agreement on a basin-wide standard in the near term
    - Potential Benefits: States begin working with Reclamation to understand current procedure benefits and downfalls; States may be able to officially accept results; States and Reclamation establish the group to assist with moving toward mid and long term options

- State Provided:
    - States perform and provide own analysis – Reclamation adopts for CU & Losses Report
    - Potential Issues: Not moving toward an approach that meets Commission Objectives of common standards. States would need to provide estimates to Reclamation in a coordinated manner along with documentation to support Reclamation reporting requirements from the Colorado River Basin Project Act of 1968.
    - Potential Benefits: There will not be competing estimates; States will be able to take advantage of more data (for example diversion records) and associated detailed procedures where available

Mid Term Options

- Same as Near Term Options (Status Quo; Status Quo Plus; State Provided)

- Reclamation Move to Penman-Monteith for Potential Consumptive Use:
    - Continue to have Reclamation perform analyses using current Indicator Gage Method to estimate actual Ag Consumptive Use
    - Use official Ag Management Group with State and UCRC representatives to establish schedules for review and coordination and provide recommendations/revisions to current Reclamation methodology including Indicator Gage method
    - Potential Issues: Need to develop new software/procedures to automate the use of Penman-Monteith; using Penman-Monteith without overhauling the method for determining Actual Consumptive Use is only addressing part of the issue;
    - Potential Benefits: States begin working with Reclamation to understand current procedure benefits and downfalls; States may be able to officially accept results; States and Reclamation establish the group to assist with moving toward long term options

- Same as previous except designate entity or consultant *other than* Reclamation to perform analysis

Long Term Options

- Use Remote Sensing to determine Actual Consumptive Use; relying on extended Station network for weather variables
  - Rely on Penman-Monteith to determine Potential Consumptive Use and associated shortages
  - Use official Ag Management Group with State and UCRC representatives to establish schedules for review and coordination
  - Potential Issues: Current higher costs associated with data processing for Remote Sensing may still be an issue in the Long Term; new procedure and standards will need to be developed; relies on satellite imagery availability on cloud-free days; may still need to reconcile results with State procedures
  - Potential Benefits: Allows one method for Upper Basin estimates; does not rely on less-accurate Indicator Gage method or installation of additional diversion measurements

- Install diversion recording devices for ditches in each State to allow for defensible, consistent basin-wide option for estimating Actual Consumptive Use
  - Rely on Penman-Monteith to determine Potential Consumptive Use and associated shortages
  - Use official Ag Management Group with State and UCRC representatives to establish schedules for review and coordination
  - Potential Issues: Significant costs associated with installation of diversion recording devices; may be legal issues in some States regarding measuring diversions; significant costs with managing diversion data
  - Potential Benefits: Allows one method for Upper Basin estimates; does not rely on less-accurate Indicator Gage method; does not rely on satellite imagery availability on cloud-free days

Technical Team Recommendations

- Discussion Item
- What does Ag Management Group look like?

Process to Secure Funding

- Discussion Item

Next Steps

  - Discussion Item

Eddy Covariance Tower Footprint Analysis

The goal is to find a daily footprint of contributing area for evaluation of ET seen by the eddy covariance tower representing all daytime hours and to allow interpolation between days of satellite overpass.

First, we will use the Schmid (1994) model to find a footprint corresponding to each 30 minutes during daytime hours. This measurement period was chosen because the eddy covariance analysis uses a half-hour averaging period. The Schmid (1994) model produces an oval footprint that is represented by two half-ellipses. Each footprint is to be rotated by the mean wind direction corresponding to that half-hour time period.

Georeferencing the footprint is an ongoing effort. To georeference the footprint, the land surface will be symbolized as a matrix where each entry in the matrix corresponds to a Landsat 30-m by 30-m pixel. For each day, we will count the number of times a given pixel was found to be in the footprint. Then we will obtain a weighting matrix for the area surrounding the tower for each day. The final output will be a weighting matrix for each day that corresponds to the pixels in a Landsat scene. The daily weighting matrix will be produced by the HEI team and distributed to the remote sensing group. The weighting matrix times the ET from each Landsat pixel in the vicinity of the EC tower will produce the EC tower ET estimated by the remote sensing method. This final calculation will be made by each team doing the remote sensing analysis.

Schmid. H.P. 1994. Source areas for scalars and scalar fluxes. *Boundary-Layer Meteorology*, 67: pp. 293-318.

Draft Outline: UCRBC Remote Sensing Report

1. Executive Summary
2. Project Objectives
3. Brief Description of Remote Sensing Methods (approximately one-half page per method plus a table comparing all methods)
    a. R-METRIC
    b. R-ReSET
    c. SSEBop
    d. ALEXI/DisALEXI
4. Operational Requirements for Each Method (e.g. computer hardware, software, storage requirements, approximate processing time per scene)
    a. R-METRIC
    b. R-ReSET
    c. SSEBop
    d. ALEXI/DisALEXI
5. Operational Difficulties
    a. Cloud cover
    b. Missing meteorological data
    c. Interpolating between days of satellite overpass
    d. SLC failure for Landsat 7 data
    e. ???????
6. Comparison of ET Estimates with Colorado Eddy Covariance Tower
    a. Description of Tower Location and Operation
    b. Description of Tower Footprint Analysis
    c. Results for Each Method – Cumulative Remote Sensing Footprint ET vs Tower ET
7. Comparison of Cumulative ET for Irrigated Lands by State for Each Method
    a. Description of Method to Compute Cumulative ET Volume by State
    b. Results for Each State
8. Discussion and Conclusions
    a. Practicality of application of remote sensing methods for evaluation of ET in the Upper Colorado Basin States
    b. Operational Requirements – Equipment, Personnel, Time

    c. Positives and Negatives of Each Method in an Operational Mode

9. Appendix I – Description of Remote Sensing Methods (up to 2 or 3 pages per method, as needed)
    a. R-METRIC
    b. R-ReSET
    c. SSEBop
    d. ALEXI/DisALEXI
10. Appendix II - ?????

Timetable: UCRBC Remote Sensing Report

30 Sep – Draft of text of various sections of report – not including results

15 Oct – Preliminary quantitative results for growing season 01 Apr to 30 Sep.

30 Oct – Final or near final quantitative results for growing season 01 Apr to 30 Sep

15 Nov – First draft of final report including quantitative analysis

30 Nov – Second draft of final report

15 Dec – Final report submission

URS

MEETING NOTES
ESTIMATION OF ACTUAL EVAPORATRANSPORATION
OCTOBER 5, 2015, 10:30 A.M. - 3:30 P.M.
CITY OF DENVER CONFERENCE ROOM, MAIN CONCOURSE, DENVER INTERNATIONAL AIRPORT
DENVER, CO

Meeting Participants:
Brenna Mefford, Wyoming
Chad Higgins, Oregon State
David Eckhardt, Bureau of Reclamation
David Merritt, AECOM
Don Ostler, Upper Colorado River Commission
Erin Wilson, Wilson Water
Greg Gates, CH2M
Jim Prairie, Bureau of Reclamation
Jody Glennon, AECOM
John Longworth, New Mexico
Kara Sobieski, Wilson Water
Kevin Flanigan, New Mexico
Kib Jacobsen, Bureau of Reclamation
Michelle Garrison, Colorado
Mike Sullivan, Colorado
Richard Cuenca, Hydrologic Engineering, Inc.
Robert King, Utah
Steve Wolff, Wyoming

Meeting Start and Introductions
David Merritt opened the meeting, reviewing the agenda (Attachment A) and referencing the Draft Memorandum of Agreement (MOA), both of which were available as handouts at the meeting. David reminded the meeting participants that the MOA was a work in progress and that the version available at the meeting did not yet include Don Ostler's recent edits and comments.

Remote Sensing Update
David introduced Dr. Chad Higgins and turned the floor over to Chad. Chad's presentation followed his "Eddy CoVariance Measurements of Evapotranspiration in Silt, CO" PowerPoint included as Attachment B.

Chad stressed that his group never sends just one person into the field; tower visits always include a small group for health and safety purposes.

Chad discussed the three evapotranspiration measurements (LE=Rn-G-H): mass conservation, energy conservation, and transport pathway. The first two of these methods are energy-balance techniques; the Eddy Covariance technique looks at transport pathway. The latter method typically underestimates evapotranspiration whereas the others (e.g., satellite techniques) typically overestimate it.

Chad emphasized the importance of quality checking all phases of each study. Quality assurance steps involve data checks, taking extra measurements (typically associated with field measurements), and math checks. Another data quality assurance process does exist but the cost is about double our costs as the tower flux has to be measured at two heights versus one.

The flux footprint allows us to back track fluid trajectories. Where the flux comes from is the footprint of the tower and is always upwind of the tower. Axes are defined by wind direction; width and length are dependent on total wind speed, turbidity, and atmospheric stability (e.g., at night, the atmosphere is stable; during the daytime, the atmosphere is unstable). The flux footprint is different for every 30 minutes of measurements. On the graphs Chad presented, the station is located at 0, 0.

Flux is desired to be north of the tower (so wind predominately from the north) – Chad indicated about 84% of the time, the wind is blowing from the north at the Silt, Colorado tower (as to the east and west are mountain ranges). There is an approximate 95% confidence interval that the footprint is based on; although one can infer grass height, it is physically measured for verification purposes.

The costs presented on Chad's slides were verified about three months ago. The tower takes measurements every 50 milliseconds.

Campbell and Licor are two manufacturers for Sonic and IRGA. Campbell is on the Silt tower; Chad selected it as it is cheaper and fully integrated (although Licor does allow Ethernet connections while Campbell does not). The aluminum towers are 30 feet tall. Satellites provide the quality check step for ensuring measurements are being taken. Chad indicated one does not operate a tower unless raw data or at least six numbers can be sent back.

Footprints are typically 100-500 meters. In the case of the Silt tower, Chad's team surveyed 500 meters. For upkeep of towers, reagents should be replaced once per year; desiccant packs should be replaced as needed, and probably once a year; data cards should be replaced as frequently as once per month; and the system should be recalibrated as recommended. Additionally, tower sites need to be groomed/weeded, and a battery maintenance schedule implemented. Towers require regular cleaning and do have built-in defrost. Data cards can get too hot and fail. One gigabyte of data is about 14 days. For tower orientation, the sensor is pointed one direction and a sector behind the sensor/tower shadow is delineated. For the tower in Silt, Colorado, the shadow corresponds to 12%.

Chad mentioned that should a migratory bird protected under the Endangered Species Act take up residency on a tower, an entire project could be halted until the young had fledged.

Chad often attaches American flags and decals to towers as those actions have deterred local interference/shooting. Chad recommends locating towers out of major lines of sight to help minimize vandalism and theft.

In reviewing the graphs in Chad's presentation, he communicated data gaps are often caused by anomalies like insects, which can cause a ping in absorption, data card failures, etc. From a quality assurance perspective, spikes are removed from the data sets along with the tower shadow. Chad communicated that if data is within 20% of the satellite reading, you are doing well.

Lysimeters are the only option for absolute error and are representative of an entire field. The advantage of large lysimeters is that they minimize edge effects; the disadvantages are the cost (about $40K to install) and the fact that they are not portable. Smaller lysimeters, although cheaper, have edge effects. To the team's knowledge, one lysimeter is installed in Arkansas and none exist in Oregon.

For labor cost estimates that appear on Chad's slides, he assumed $100 per hour, per person. Chad indicated quality assurance/quality checks are typically performed by a person with a master's degree or in the master's program. If one is within 15% on energy balance checks, they are well within the tolerance for successful Eddy CoVariance Tower operation.

Overall, 80% of the data collected is good/usable and typical. Without a data card failure, Chad likes to be above 90%. Throughout the entire growing season, it looks like about a half meter of water came off the field, which is within the team's expectations. ***For the final report, Chad will fill in the data gap based on an average.***

During the lunch intermission, Chad offered live plotting for those interested.

Site Selection Discussion
Following lunch, Chad led a discussion on site selection, including site criteria and selection strategies.

Chad deferred to the State representatives on site selection input since they know their respective geographies the best. A decision needs to be made on strategy. Sixteen scenes in an area would require 32 towers, but scenes do overlap. Hot pixels assume very little to no evaporation; cold pixels have maximum evaporation.

Chad indicated representative areas would typically be those with the highest land coverage. Jim Prairie envisioned the tower as a ground truth, or way to verify reasonable estimates from other techniques. Erin Wilson responded that may mean putting the towers in more stressed areas. ***Chad asked the meeting participants to consider the four strategies for a tower network (i.e., maximize the number of scenes; optimize placement in scenes [hot/cold pixel idea]; maximize representative areas; and increase coverage or utility of agriculture weather network), and to e-mail him with suggestions/ideas for setting goals.*** The current funding allows three to five stations versus 16. It was suggested that the towers be left in place for three to four years and then move them to a new area. Chad indicated he originally thought there were benefits to leaving a tower somewhere for multiple years to capture climate changes, but his thinking has changed based on how quickly the system can "learn" based on his tests. As the team knows, site conditions are static conditions and climate and runoff conditions play a large role in the results.

The team clarified that Eddy Covariance Towers are not needed for remote sensing – they are needed for ground truthing. ***Chad will develop recommendations for tower locations. A draft report is scheduled to be released around the end of October.***

Remote Sensing of Actual Evapotranspiration Discussion
Dr. Richard Cuenca led a discussion that followed his "Remote Sensing of Actual Evapotranspiration" PowerPoint included as Attachment C. Richard indicated downloads through September 28, 2015, are available, but he is not at the point where methods can be compared yet. Richard indicated NASA and the USGS have started work on Landsat 9, planned to launch in 2023, which will extend the Earth-

observing program's record of land images to half a century. Landsat 7 and 8 record data every 16 days, giving us coverage every 8 days combined.

Richard walked the meeting participants through his slides. Following the download of scene selections, algorithms are run. The light blue pixels indicate areas that passed the limits for cold pixel selection; red pixels indicate areas that fall within the criteria for hot pixel selection. The large red areas seen on the slides are clouds (Richard noted those will appear black in future iterations). The red lines denote Landsat 7 failure lines. Cold and hot pixels in close proximity to weather stations are identified. Pixels are selected based on their bracketing ability for evapotranspiration. Richard clarified that a pixel does not have to be a non-irrigated field, but he suggests it. Hot pixels should reflect zero or minimum evapotranspiration. A different hot and cold pixel is typically chosen for every scene. Flat line data readings typically mean there is a problem with a sensor (e.g., it got taken off-line).

The source of crop data is the Naval Oceanography Command Detachment (NOCD) designation. Brian Westfall with Keller-Bliesner provided Erin Wilson with a crop data contact at Navajo but she has not heard anything back from that person after multiple e-mail and call attempts. The team has not looked at valleys or sub-scenes. Evapotranspiration can be looked at per growing season and can be separated out further by crop. ***The team is working on getting all of the hourly data from the Block 1 Station.***

Richard recommended obtaining the ESPA file, the text file used to download scenes, to see if there are improvements, and then re-running the Landsat 8 data using the new OLI albedo coefficients.

Draft Outline, Revised October 4, 2015, Discussion
Richard presented the draft outline of the UCRBC Remote Sensing Report. For the remote sensing methods listed, Richard clarified that 3a and b (i.e., R-METRIC and R-ReSET) require hot and cold pixel selection, whereas 3c and d (i.e., SSEBop and ALEXI/DisALEXI) do not.

Richard indicated he does not favor ensemble means; however, because some team members indicated it would be nice to test those, he will. He will also compare the different methods by State. Richard estimates it takes about a day, something on the order of 8 hours, to analyze a scene.

Richard shared his recent NASA QNC (qualified non-crew) experience with the group. Each site requires four flight lines at 41,000 feet. The tube is 2 meters high by 2 meters wide. Richard wanted to make the point that data and radar systems are continuing to evolve and the team should be open to new systems/hardware/software/the way analyses are performed, and take into account two or three satellites instead of just considering one.

Meeting Summary
David took the floor and asked the team to think about where they want to go with the project in the next two to three months. ***Two draft reports are scheduled to be released around the end of October for remote sensing, towers, placement, and weather stations. From there, the team is looking at the Principal's Meeting on December 2, 2015, in Albuquerque, NM (which will be a Commission/work meeting)***. David sought recommendations regarding whether the team go forward from here with a desired model within a certain timeframe, considering the dueling model studies.

Draft MOU

David asked the team what needs to be brought forward to start implementing the methodology and the path forward for the next 5-10 years. Don Ostler then led a discussion regarding reporting that surrounded meteorological stations, installation costs, operation and maintenance (O&M) costs, and getting the go ahead to install the towers. Don communicated a second, more long-range step with regards to remote sensing, reporting that is equal to or better than what is being done now, costs, the results of the methods tested, and the best methodology. Don confirmed with the group that there have been no negative signals thus far on remote sensing, and then requested that the team identify the suite of decisions to be made. For example, is remote sensing feasible, and cost effective? What is the next step…a larger pilot program or period of time for folks to consider shifting that direction and consider funding it?

Don indicated since the time these project discussions commenced, it has become clear that a more formal arrangement is needed for operating, maintaining, and sharing responsibility for keeping the towers running; thus, the proposed MOA between the four Upper Division states, UCRC, and Reclamation. The draft MOA that was available at the meeting addressed meteorological stations and the overall goals and objectives that the Commission gave the team when it provided the go ahead for starting the Phase I and II reports.

The objective of the MOA is for the Upper Division states and Reclamation to acknowledge the resources that need to be committed to the upkeep of the towers. The October 5th meeting was the first time the group had seen the MOA; Dave, Erin, and Jim developed the first draft with comments from Don. ***David requested that folks review the MOA and e-mail him edits/comments/suggestions/etc.*** The Parties to the MOA are the four Upper Division states, Reclamation, and UCRC. The current MOA identifies short-, mid-, and long-term goals.

The question was asked: do we really need an MOA -- won't the UCRC support the needed actions? David explained that scopes of work will establish the various commitments. UCRC can direct the team on what to do but it cannot tell Reclamation what to do. The MOA, then, provides a tool for committing Reclamation to working with the UCRC. Don indicated it is important to establish the MOA now and prior to future agency turnover. Don reiterated that the MOA would tie UCRC and Reclamation together.

Erin explained that part of the frustration is that the states are not willing to review and approve/stand behind the actions. Erin further explained that the MOA provides a tool for internal use within Reclamation for funding, resources, agreement on consumptive use calculations, etc. It establishes a formal partnership.

Michelle Garrison indicated she would talk to her legal staff about the MOA and did not have any concerns with expanding the MOA beyond agricultural consumptive uses. Michelle did indicate it would be good to understand Reclamation's efforts.

It was stated that MOAs do not make things go smooth but they do typically make them go better. Don indicated he would like to get the meteorological stations installed and believes the team needs an agreement in place for those to be installed and supported by the states. Don felt because each state would be committing financial and resource support, each Commissioner, along with Reclamation, would need to sign the MOA.

It was suggested that a section be added to the MOA to enable a means to add and subtract from it, acknowledging a process for the Commission to make modifications to it. Robert King suggested adding or modifying the existing language to extend the limits of the MOA. For example, the team does not want to have to amend the MOA to add a task. Instead, the MOA should identify a process (e.g., require a letter signed by all Parties, etc.). Also, upon notification, can the MOA be terminated? In recognizing independent authorities, it is anticipated that contingency language will be added by the various legal groups (so better to engage legal staff early). Should the MOA be more restrictive or more general? The word “consensus” is used throughout; its use was intended to indicate “no objection” but its use will be revisited. Additionally, the MOA will be reviewed and updated to ensure it does not contain a pre-decisional tone.

As the MOA discussion progressed, the team thought it might be more appropriate for the near-term MOA to contain information on specific near-term decisions that are needed and include more vague information for the mid- and long-term. In other words, the MOA should provide initial direction with other tasks being added later on. For example, the climate stations could start to be installed now if resource support was in place. The team lacks the go ahead from the UCRC; funding is sitting there; and approval from the Principals is in place, but Don and others worry about the capital investment of installing stations without O&M agreements and resource allocations in place – risky! Utah is willing to pay/cover O&M costs of stations in its state, but Colorado and New Mexico are not able to do that due to funding. Reclamation has committed to 1/5 of costs or roughly $37K for installation and first-year maintenance costs.

Don has a feeling of uncertainty in regards to how long it is going to take to get MOAs in place. He suggested a simple MOA for station installs now, and then work on a second, more detailed, longer-term MOA. The simple MOA would be a cut-down version of the existing MOA to remove funding but leave the cost elements in. The long-term MOA would be a commitment to a common set of tasks and be resource driven. Chad noted a third MOA, or an amendment to the first MOA, may be needed for the Eddy Covariance Towers.

Don indicated the team has minutes from a meeting in which the Commission agreed to certain actions by the Steering Committee and directed the team to evaluate technical and legal parts. Don suggested the team review those minutes. The simple MOA would then take general direction from those minutes in order to be consistent with it. There is a requirement to look at what the team can improve. Don stressed the need for the states to approve certain actions soon for mid-term accomplishment – the team eventually needs to stop evaluating and “do.”

The MOAs discussed will be redrafted into separate MOAs and be made available in time for the October 19, 2015 conference call. David released a conference call invite on October 6, 2015, to schedule a follow-up discussion on the MOAs. *The follow-up MOA call will take place on Monday, October 19, 2015, from 4-5 p.m. Mountain.*

Don indicated the siting study results need to be presented to the Commission in order for the remaining installs to occur; based on that, the remaining installs are anticipated in the spring of 2016.

Closing

The 2006-2010 Consumptive Uses and Losses data will be sent out by Jim soon, along with the spreadsheets that support those consumptive use calculations.

ATTACHMENT A

DRAFT AGENDA
ESTIMATION OF ACTUAL EVAPORATRANSPORATION
5 OCTOBER 2015
1030 AM- 3PM
CITY OF DENVER CONFERENCE ROOM
MAIN CONCOURSE
DENVER INTERNATIONAL AIRPORT
DENVER, CO

Remote Sensing Update

1.	**Discussion of Eddy CoVariance Tower Operations**	**Dr. Chad Higgins**
2.	**Potential number of towers needed.**	**Dr. Chad Higgins**
3.	**Discussion of Model Comparisons**	**Dr. Richard Cuenca**
4.	**Discussion of Operations needs**	**Dr. Cuenca & Higgins**

Potential Memorandum of Agreement for Program Operations

Next Tech Team Meeting

Meeting with Principals

URS Corporation
804 Colorado Avenue, Suite 200
Glenwood Springs, CO 81601
Tel: 970.384.4738
Fax: 970.945.9182

ATTACHMENT B

Eddy Covariance Measurements of Evapotranspiration in Silt, CO

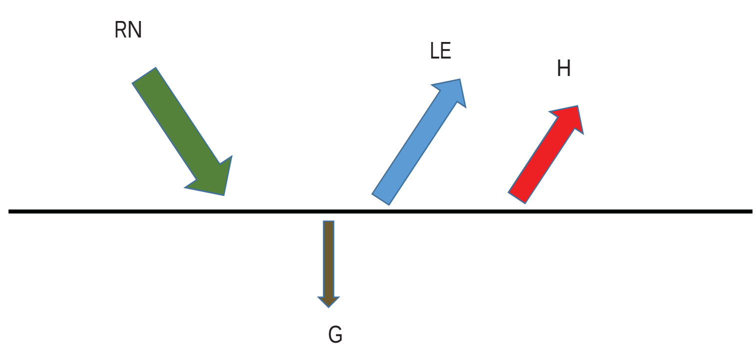
Chad Higgins

Preliminary findings subject to change

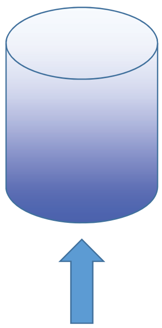
ET measurement

- Energy balance techniques vs. eddy covariance

LE=Rn-G-H

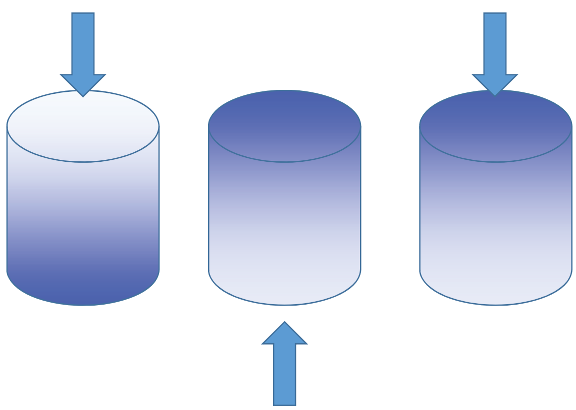


Concept of eddy covariance (advection)



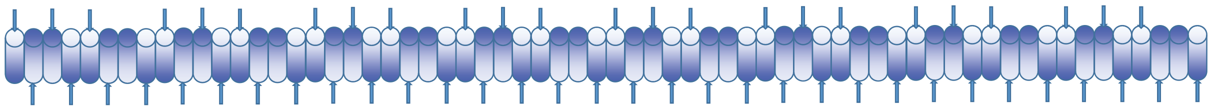
Relatively wetter air (q') moved upward by a relative vertical velocity (w') creates a positive flux of water vapor, this is denoted as w'q'. When q' is measured in mass/volume, this quantity is the evaporation

Concept of eddy covariance (advection)



3 other potential combinations: dry moving down, dry moving up, and moist moving downward. These represent positive, negative and negative water vapor fluxes respectively

Why covariance?



Can envision the atmosphere as composed of many such upward and downward motions. Each motion moves a moisture upward or downward, and is associated with a discrete flux w'q'. We want the average flux, so we have to sample an adequate amount of these events and average:

$\langle w'q' \rangle$ ← That is the definition of covariance

Eddy covariance equations, assumptions, and checkable assumptions

$$\frac{\partial q}{\partial t} + \frac{\partial uq}{\partial x} + \frac{\partial vq}{\partial y} + \frac{\partial wq}{\partial z} = \upsilon\left(\frac{\partial^2 q}{\partial x^2} + \frac{\partial^2 q}{\partial y^2} + \frac{\partial^2 q}{\partial z^2}\right)$$

Advection Diffusion Equation

$$\frac{\partial q}{\partial t} + \frac{\partial uq}{\partial x} + \frac{\partial vq}{\partial y} + \frac{\partial wq}{\partial z} = 0$$

Assume Advection>>diffusion

$$\frac{\partial q}{\partial t} + \frac{\partial wq}{\partial z} = 0$$

Assume Horizontal homogeneity

$$\frac{\partial(\langle q \rangle + q')}{\partial t} + \frac{\partial(\langle w \rangle + w')(\langle q \rangle + q')}{\partial z} = 0$$

Reynolds decomposition

$$\frac{\partial(\langle q \rangle)}{\partial t} + \frac{\partial q'}{\partial t} + \frac{\partial(w'\langle q \rangle)}{\partial z} + \frac{\partial w'q'}{\partial z} = 0$$

Assume mean vertical wind is 0

Eddy covariance equations and assumptions

$$\left\langle \frac{\partial(\langle q \rangle)}{\partial t} + \frac{\partial q'}{\partial t} + \frac{\partial(w'\langle q \rangle)}{\partial z} + \frac{\partial w' q'}{\partial z} \right\rangle = 0$$

Take the average

$$\frac{\partial(\langle q \rangle)}{\partial t} + \frac{\partial \langle w' q' \rangle}{\partial z} = 0$$

Assume stationarity

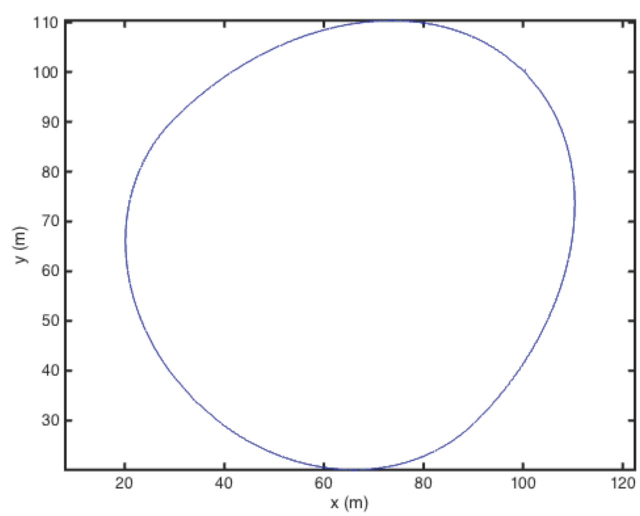
$$\frac{d\langle w' q' \rangle}{dz} = 0$$

Integrate

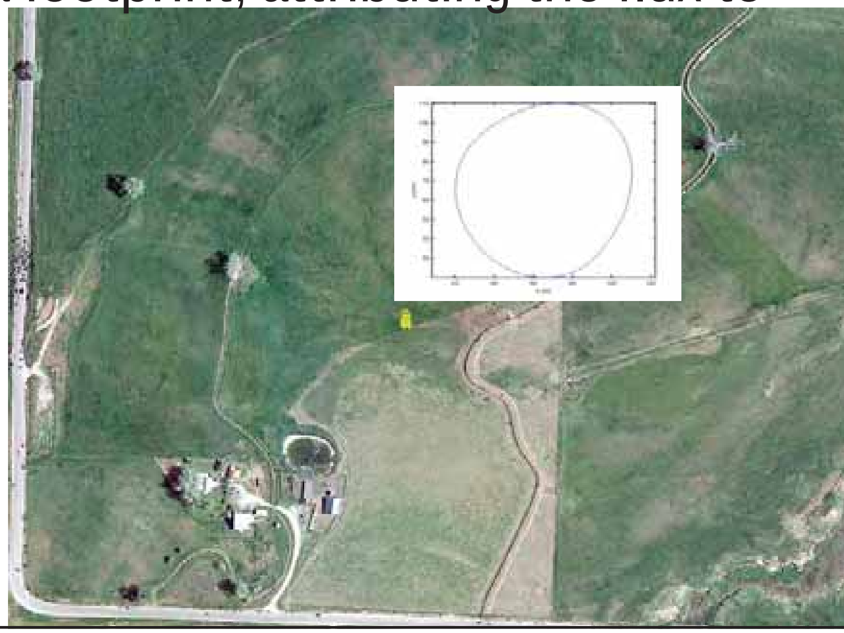
$$\langle w' q' \rangle = c$$

Measured flux is surface flux

Flux footprint (attributing the flux to an area)



The idea of a footprint, attributing the flux to a pixel(s)

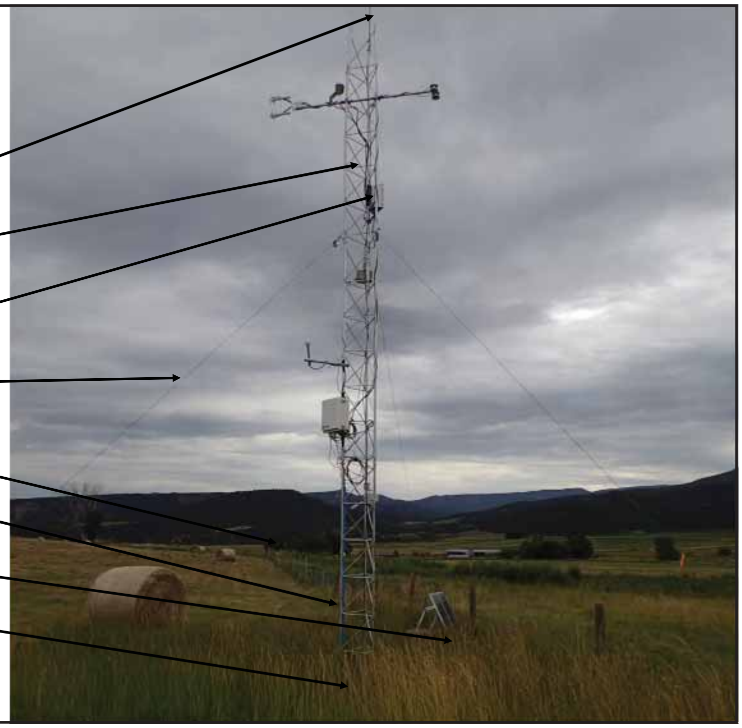


Tower anatomy, recommended setup (sensors)

- Sonic and IRGA
  - Campbell $20k
  - Licor $25k
- Logger
  - CR1000 $1.5k
  - CR6 $1.5k
  - Licor logger
- Aftermarket mods
- T+RH (included)
- Radiation ($2k)

Tower anatomy, (infrastructure)

- Grounding $800
- Tower ~$1.5k
- Electrical isolation $50
- Fixation $200
- Fencing $1k-$3k
- Cable care $100
- Power system ~1k
- Base $200
- Wildlife management



Tower anatomy, recommended setup (telemetry)

- Radio
- Cell (could be a criterion for site selection) $80/month
- Satellite – what we used, 6 numbers per hour, $25/month
- Wireless internet $80/month

Tower anatomy, recommended setup (site survey)

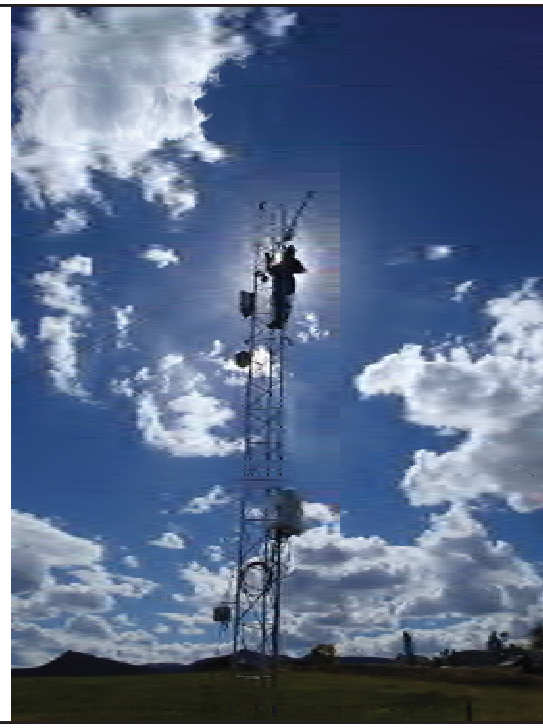
- Instrument heights and location
- Local land features
- Grass height
- Abrupt changes in land surface that may be in a tower footprint (Higgins et al 2012)

Tower anatomy, Recommended maintenance

- Reagents
- Desiccants
- Data cards
- Recalibration
- Vegetation control (solar power in particular)
- Battery maintenance (extreme cold heat, battery cycling, and charging)
- cleaning

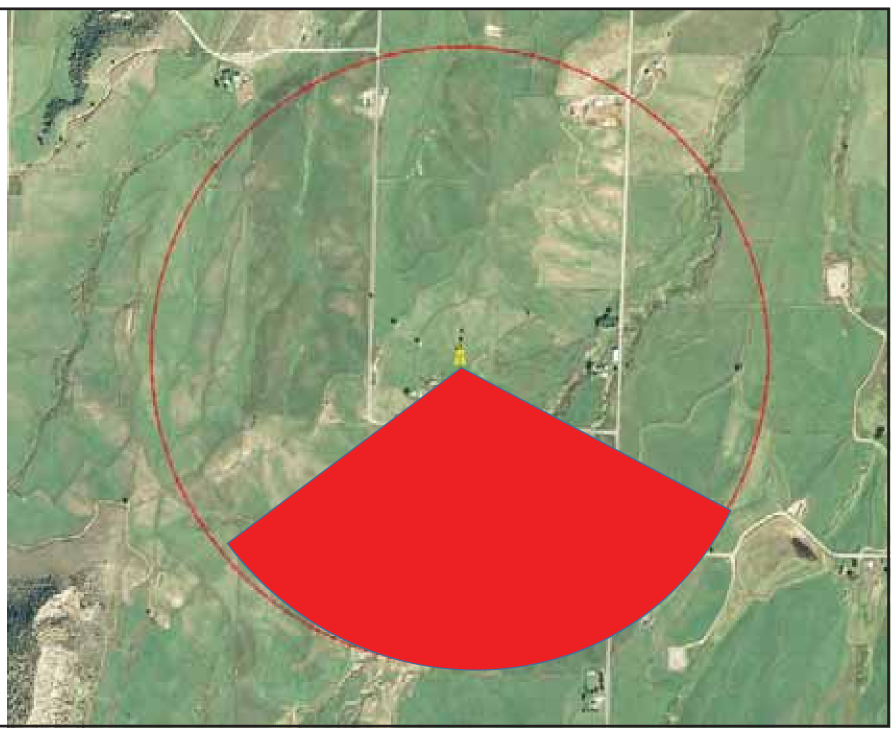
Tower anatomy, safety practices

- Hard hats
- Osha approved 3 point harness for tower climbing
- Tower climbing training/certification
- Marking of guy wires, ground obstructions etc.
- Fencing to keep unauthorized from climbing
- This is not an exhaustive list!



Tower anatomy, Tower placement

- Tower shadow
- Mode of the wind direction

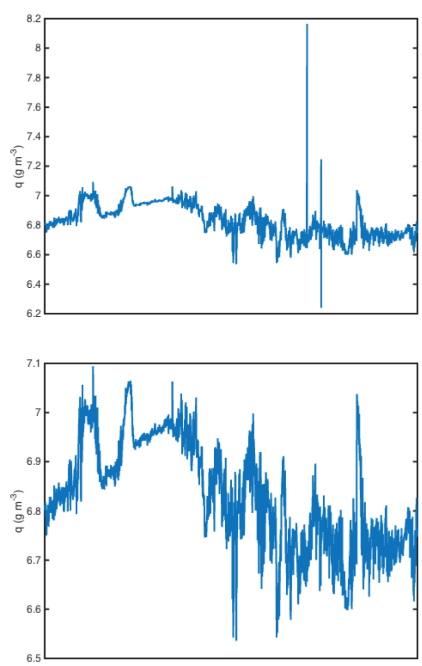


What can go wrong?

- Power failures
- Lightning
- Electronics failures
- Local interference
- Wildlife
- Farm machinery
- Vandalism
- Trees
- Insects
- Extreme weather

Data quality assurance

- Energy balance checking
- Data inspection and de-spiking
- Error flag
- Tower shadow
- Snow and rain (condensing conditions)
- Check mean vertical wind characteristics
- Check atmospheric stability
- Check stationarity
- Monitor battery voltage



Data analysis (corrections)

- Planar fit or double rotation (not a correction)
- Webb (WPL) corrections for density of air
- Sensor separation correction (only with Licor solution)
- Commercial software is available (we use our own code)
- Many other corrections are available, I prefer a minimalist approach (my opinion)

Methods for Error assessment

- Salesky and Chamecki 2013 ~10%, from the limits of the signal itself this does not count installation errors, or other user errors
- Comparisons with other methods (for context and relative error)
- Only lysimeters for absolute error

Cost estimates

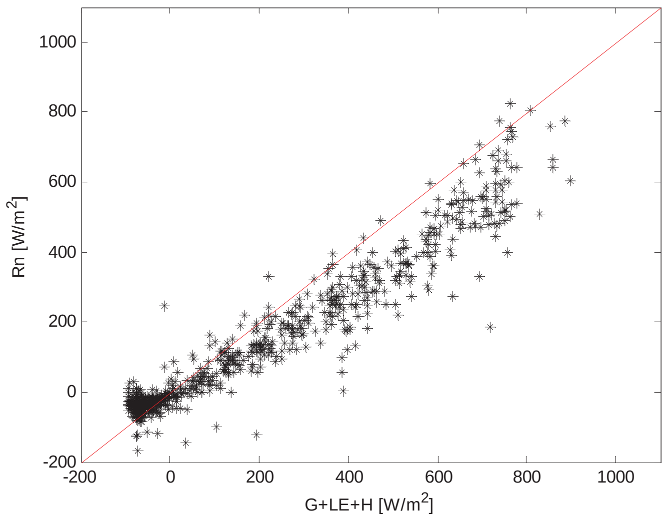
• Sensors:	$27k		
• Infrastructure:	$5k		
• Hardware:	$1k		
• Telemetry:	$1.5k +	$1k/year	
• Consumables:		$0.5k/year	
• Calibration:		$0.7k/year	0.5 person-day
• Installation:			10 person-days
• Site survey:			1 person-day
• Site maintenance:			12 person-day/year
• QAQC+analysis			0.2 FTE

$60k+
$2.3k/y

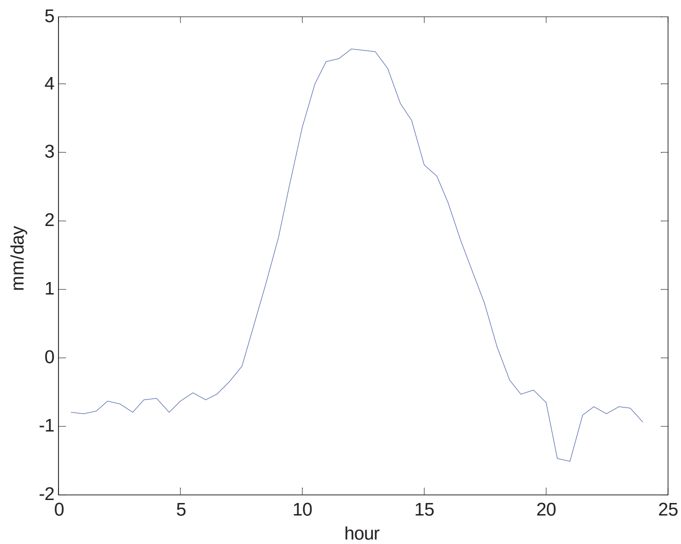
Current state of eddy covariance data

- Tower was removed on 10/4/2015 @12:30pm
- QAQC + analysis to determine flux complete, save 3 weeks of data that we acquired yesterday
- More than 50% of the data have had footprints attributed
- Still to do:
  - Georeference the footprint areas to select associated Landsat pixels
  - Compare with Richard's outputs

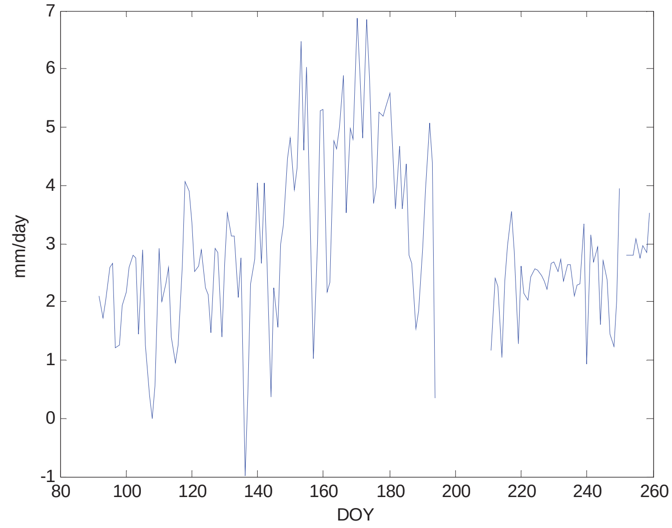
Energy Balance Check



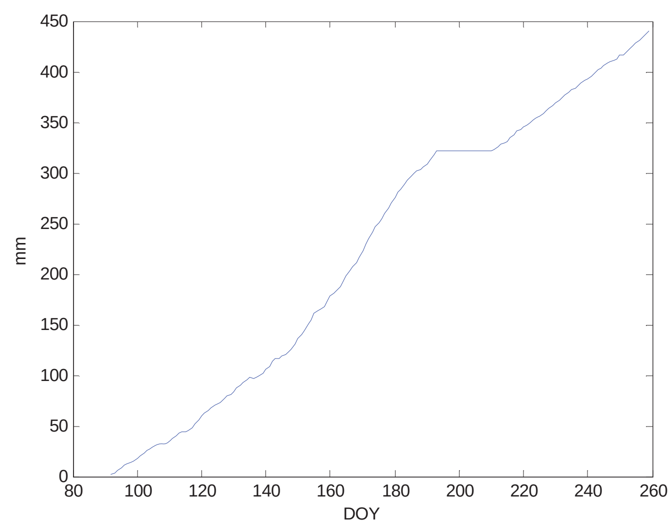
The average day



The daily average ET



Cumulative ET from April 1



Intermission…live plotting for those interested

Site Selection Discussion

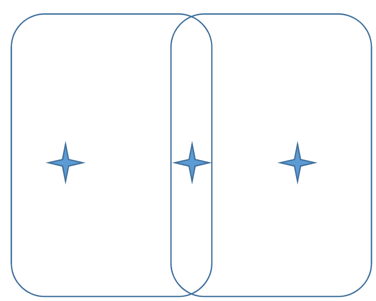
- Assume that we are trying to maximize utility of the Satellite data.
- Assume that the total number of towers is << total number of climate stations

Site selection Discussion

- Criteria for site selection
  - Flat fields
  - No overhead irrigation
  - Protection from livestock
  - Land ownership/permissions
  - Predominant wind conditions
  - Cell service
  - ‘representative’
- Critical to involve state reps.

Strategies for a Tower network

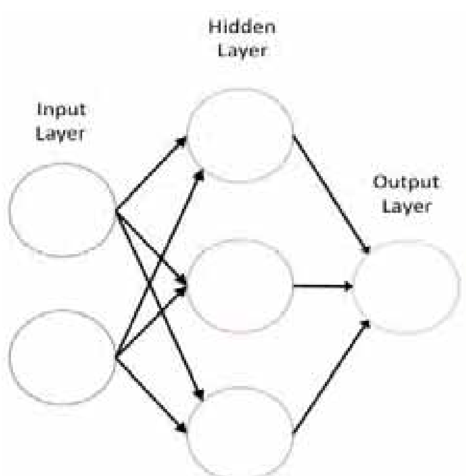
- Maximize the number of scenes
- Optimize placement in scenes
  - hot pixel/cold pixel idea
- Maximize ‘representative’ areas
- Increase coverage or utility of ag weather network.

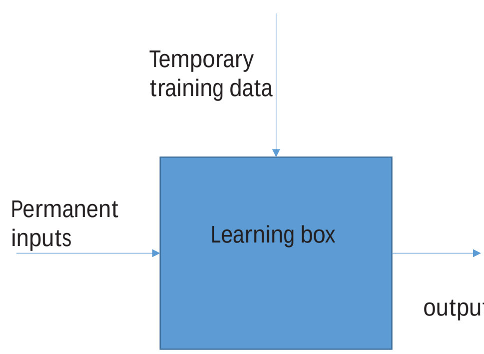


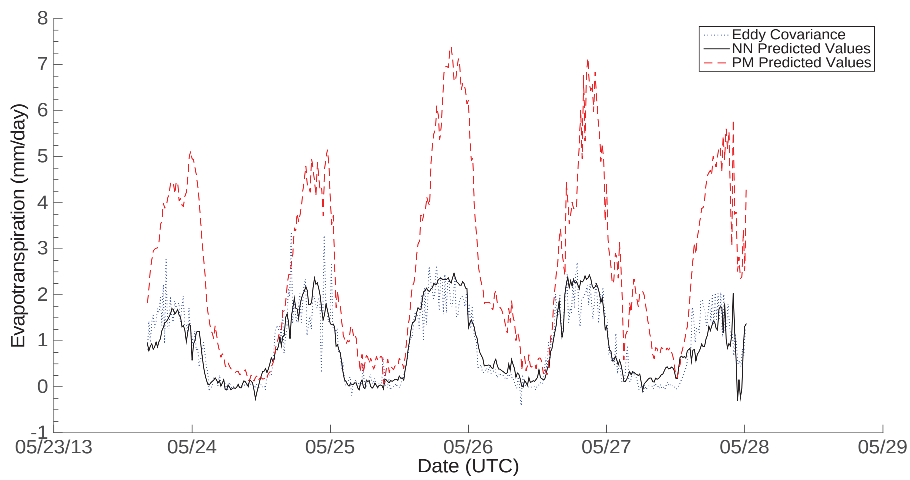
Mobile or fixed?

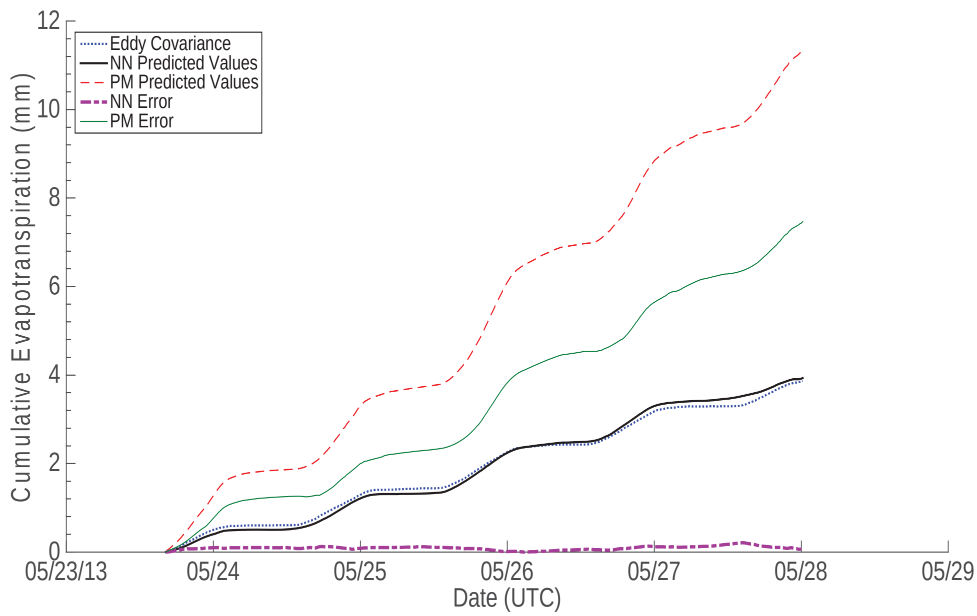
- Mobile must bring added information, not just different information
  - Adaptive neural network approach
  - Iteration with satellite team to get best adjustment through some sort of iteration
  - 'Scene chasing'

Example, adaptive neural network training of a Penman Monteith station






Eddy Covariance
NN Predicted Values
PM Predicted Values
Evapotranspiration (mm/day)
Date (UTC)
05/23/13
05/24
05/25
05/26
05/27
05/28
05/29


Eddy Covariance
NN Predicted Values
PM Predicted Values
NN Error
PM Error
Cumulative Evapotranspiration (mm)
Date (UTC)
05/23/13
05/24
05/25
05/26
05/27
05/28
05/29

ATTACHMENT C

Remote Sensing of Actual ET

Richard Cuenca Dept. of Biological and Ecological Engineering
Oregon State University
Hydrologic Engineering, Inc.

Landsat 9

April 16, 2015
15-061

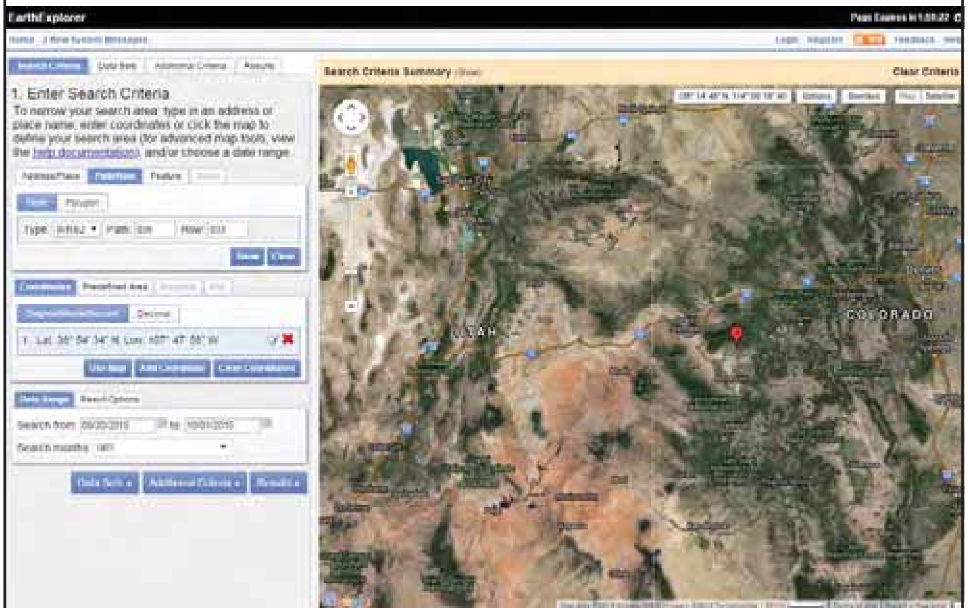
NASA, USGS Begin Work on Landsat 9 to Continue Land Imaging Legacy

NASA and the U.S. Geological Survey (USGS) have started work on Landsat 9, planned to launch in 2023, which will extend the Earth-observing program's record of land images to half a century.

The Landsat program has provided accurate measurements of Earth's land cover since 1972. With data from Landsat satellites, ecologists have tracked deforestation in South America, water managers have monitored irrigation of farmland in the American West, and researchers have watched the growth of cities worldwide. With the help of the program's open archive, firefighters have assessed the severity of wildfires and scientists have mapped the retreat of mountain glaciers.

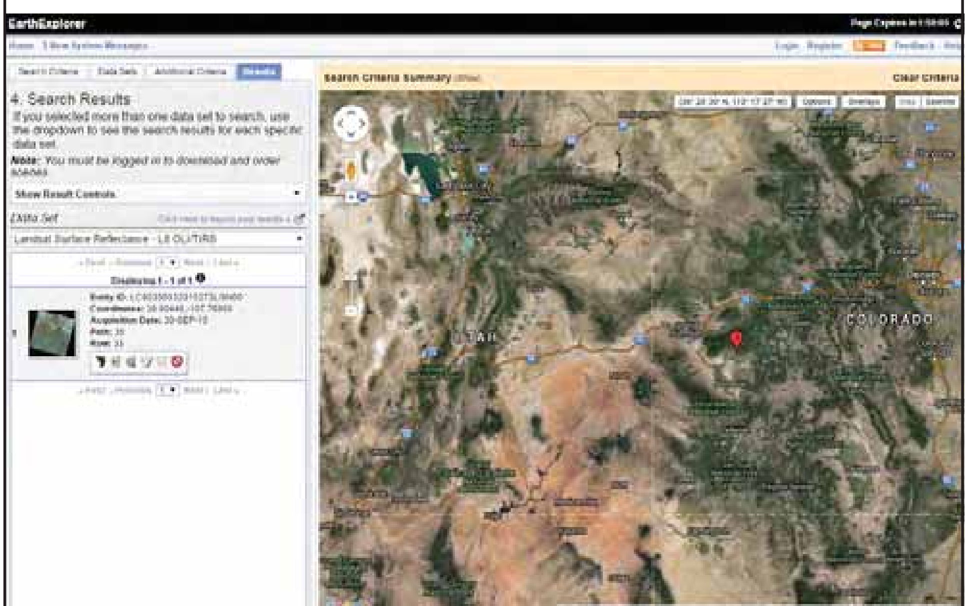
Remote Sensing of Actual ET

Selection of Landsat Scenes for Analysis



Remote Sensing of Actual ET

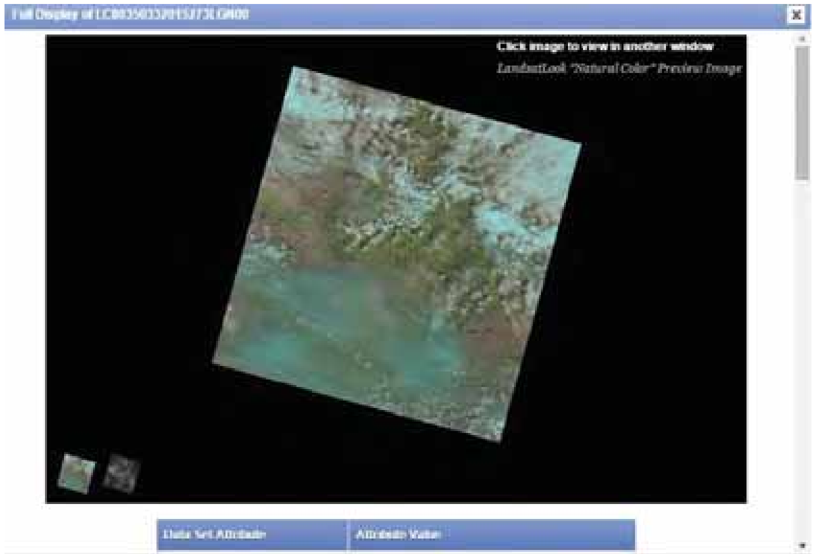
Selection of Landsat Scenes for Analysis



Remote Sensing of Actual ET

Selection of Landsat Scenes for Analysis

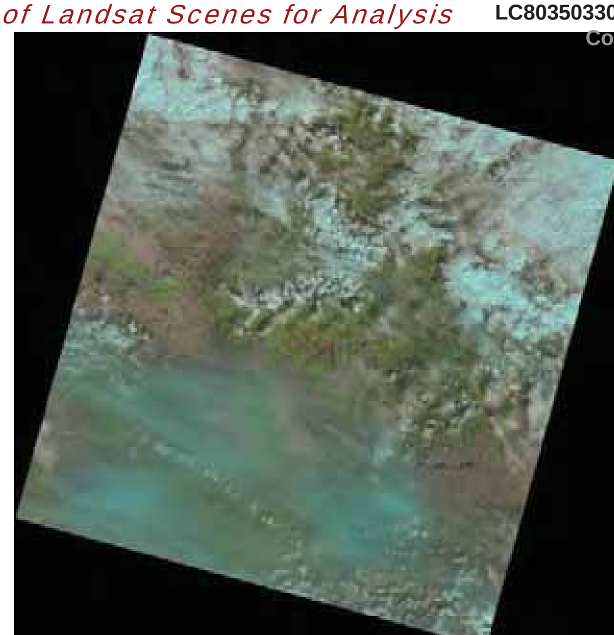
LC803503302015273LGN00
Colorado



Remote Sensing of Actual ET

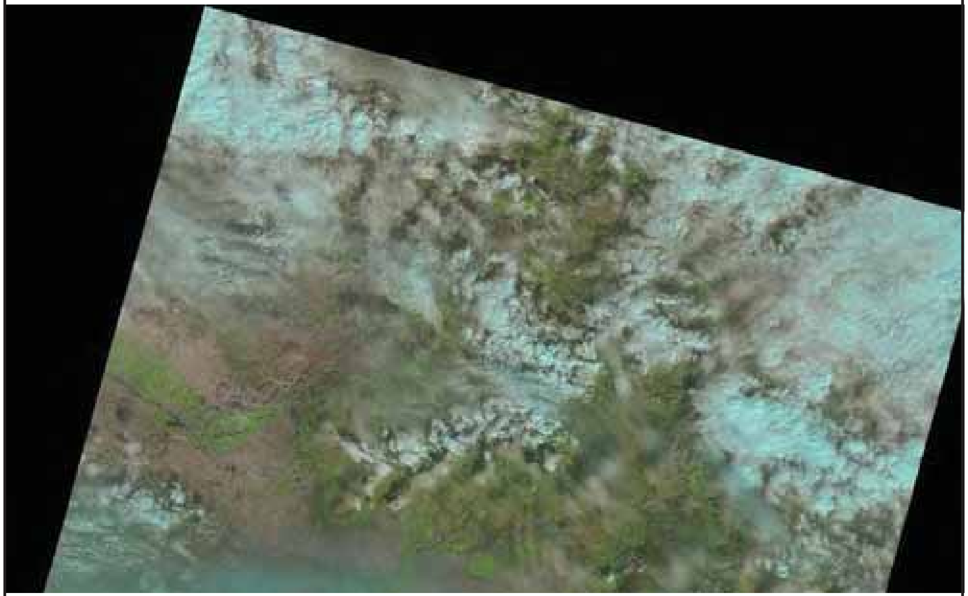
Selection of Landsat Scenes for Analysis

LC803503302015273LGN00
Colorado



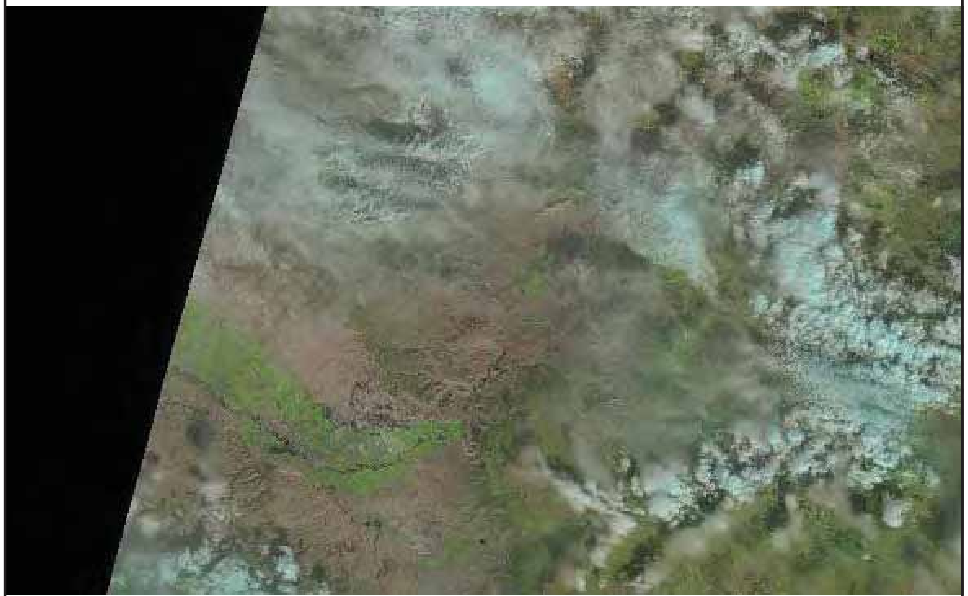
Selection of Landsat Scenes for Analysis

LC803503302015273LGN00
Colorado



Selection of Landsat Scenes for Analysis

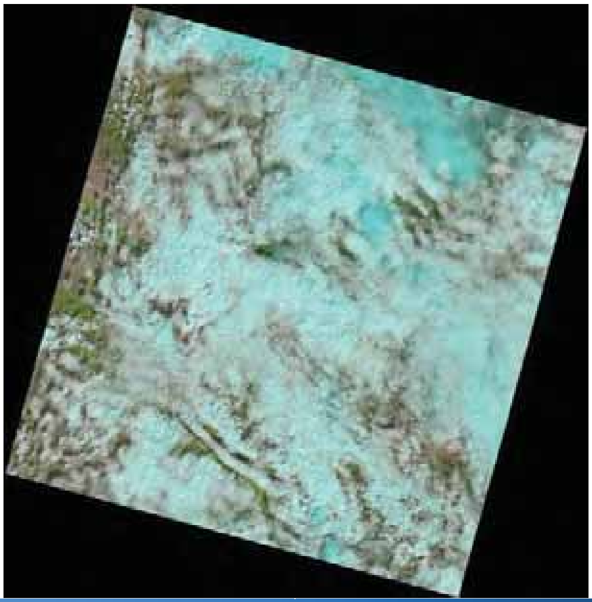
LC803503302015273LGN00
Colorado



Remote Sensing of Actual ET

Selection of Landsat Scenes for Analysis

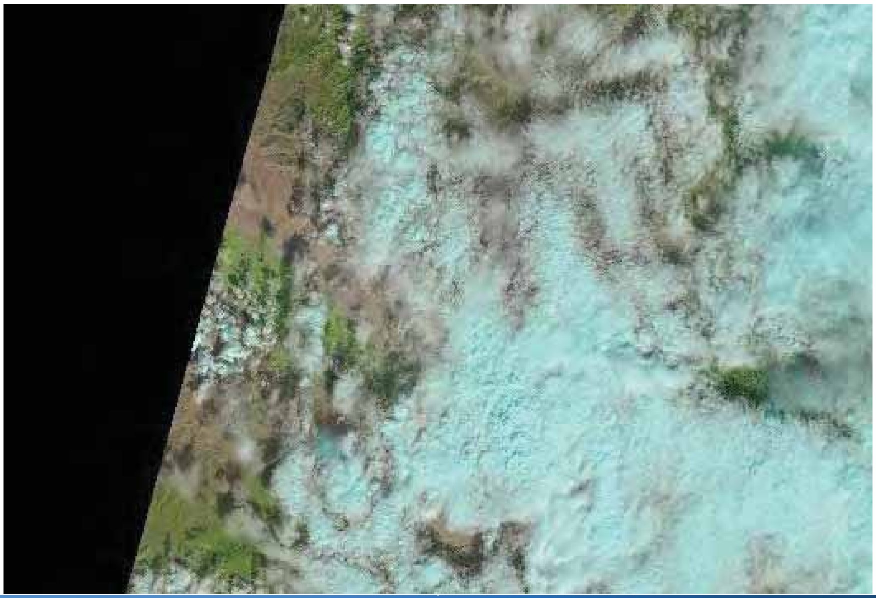
LC80350332015257LGN00
Colorado



Remote Sensing of Actual ET

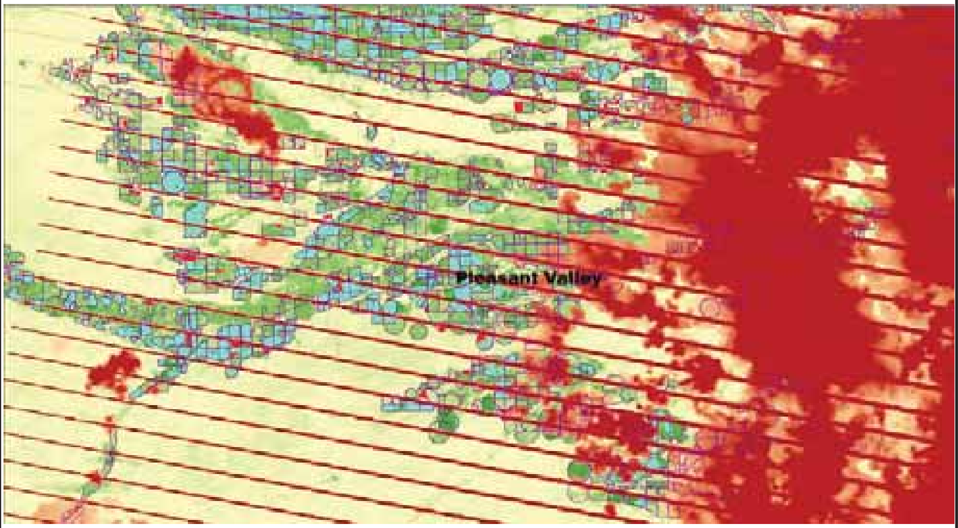
Selection of Landsat Scenes for Analysis

LC803503302015257LGN00
Colorado



Remote Sensing of Actual ET

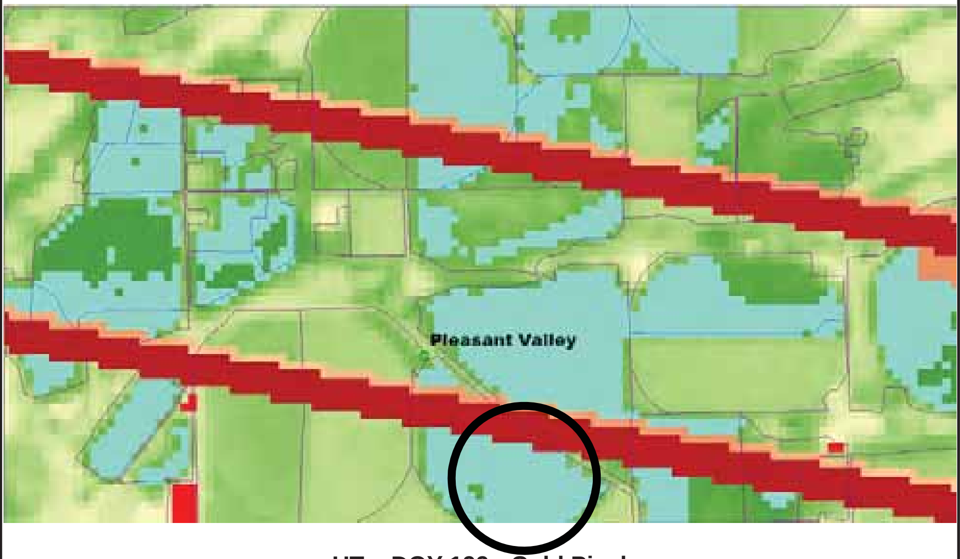
Hot and Cold Pixel Selection



UT – DOY 199: Pixel Selection

Remote Sensing of Actual ET

Hot and Cold Pixel Selection



UT – DOY 199: Cold Pixel

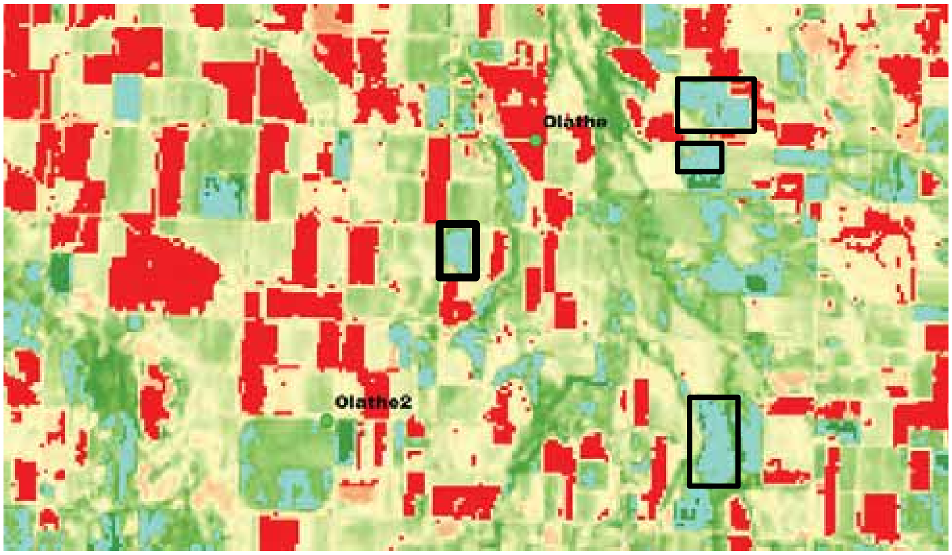
Hot and Cold Pixel Selection

UT – DOY 199: Hot Pixel

Hot and Cold Pixel Selection

CO: DOY 177 – Potential Hot Pixels in Vicinity of Olathe 2

Hot and Cold Pixel Selection



CO: DOY 177 – Potential Cold Pixels in Vicinity of Olathe 2

Remote Sensing of Actual ET

Hot and Cold Pixel Selection

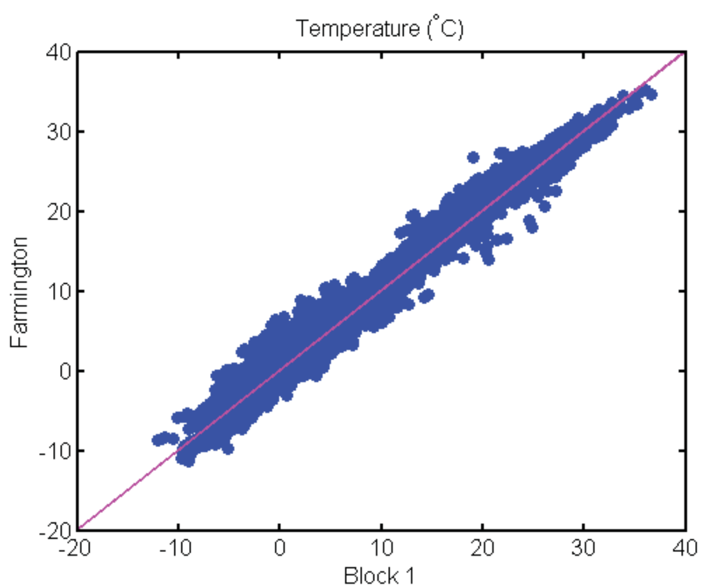
DOY	Cold Pixel							Hot Pixel						
	easting	northing	NDVI	albedo	LST	LAI	Comment	easting	northing	NDVI	albedo	LST	LAI	Comment
153	235,633	4,275,625	0.834	0.209	297.50	6.000		231,777	4,285,405	0.139	0.188	316.28	0.046	
	240,479	4,271,954	0.820	0.207	300.01	6.000		241,836	4,268,239	0.134	0.207	313.16	0.041	
	254,454	**4,302,012**	0.880	0.230	295.48	6.000		236,604	4,279,169	0.123	0.193	314.05	0.024	
	268,181	4,287,801	0.890	0.230	295.99	6.000		**233,256**	**4,278,083**	0.159	0.204	314.90	0.083	
165								233,313	4,280,996	0.169	0.248	316.70	0.094	
169	**230,938**	**4,277,142**	0.875	0.202	298.62	6.000		235,008	4,276,456	0.168	0.266	314.84	0.116	
	235,757	4,270,085	0.781	0.198	300.01	6.000		**232,989**	**4,276,677**	0.156	0.274	317.57	0.092	
	231,319	4,275,535	0.885	0.242	298.01	6.000		232,982	4,276,482	0.159	0.278	317.57	0.099	
	236,373	4,273,961	0.790	0.192	301.48	6.000		237,405	4,279,802	0.171	0.230	316.28	0.114	
	235,765	4,280,065	0.843	0.193	301.00	6.000								
177	**233,874**	**4,279,781**	0.906	0.217	302.49	6.000		231,606	4,279,532	0.219	0.230	314.84	0.210	
	236,035	4,278,010	0.816	0.169	302.09	6.000		232,381	4,277,284	0.144	0.262	312.66	0.069	
	236,197	4,280,919	0.889	0.181	304.33	6.000		**232,924**	**4,276,519**	0.182	0.195	316.77	0.123	
	235,996	4,280,551	0.917	0.197	301.65	6.000								
185							Clouds mask cold pixels							Clouds mask hot pixels
193	**232,581**	**4,277,785**	0.909	0.197	296.04	6.000	Near Olathe 2	**236,635**	**4,280,351**	0.170	0.171	308.45	0.092	
201	**230,458**	**4,290,812**	0.814	0.217	288.70	6.000	Delta least affected by clouds	**228,768**	**4,290,097**	0.185	0.210	302.48	0.135	Delta least affected by clouds

Remote Sensing of Actual ET

Farmington vs Block 1 Meteorological Data, NM

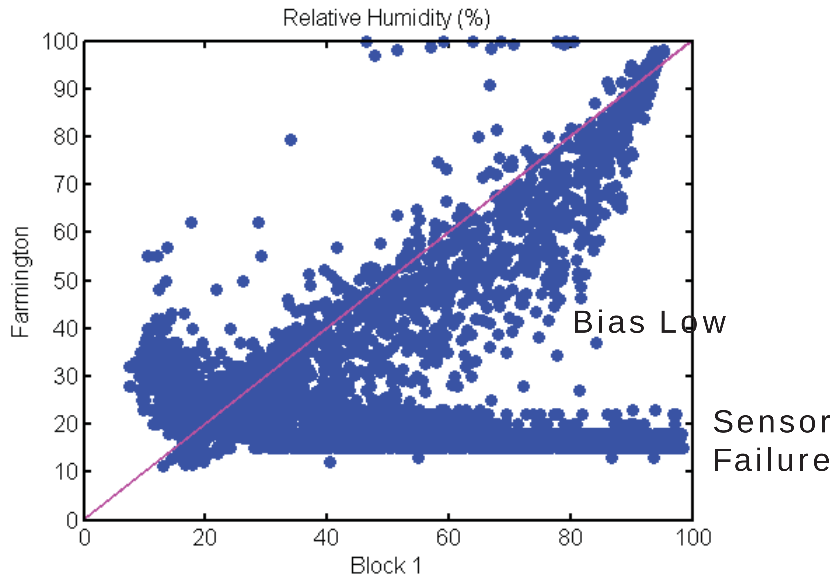
Remote Sensing of Actual ET

Farmington vs Block 1 Meteorological Data – Hourly T_{air}



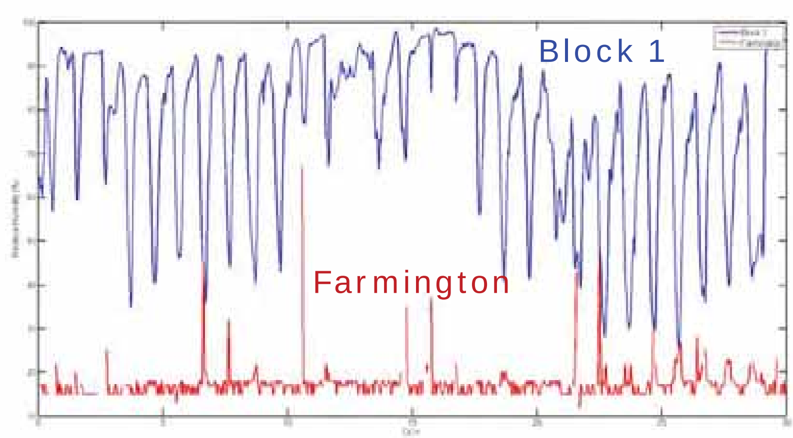
Remote Sensing of Actual ET

Farmington vs Block 1 Meteorological Data – Hourly RH



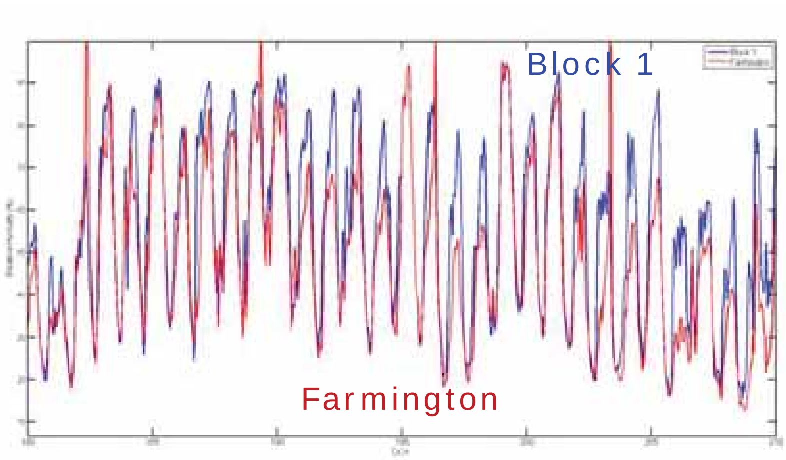
Remote Sensing of Actual ET

Farmington vs Block 1 Meteorological Data – RH Times Series



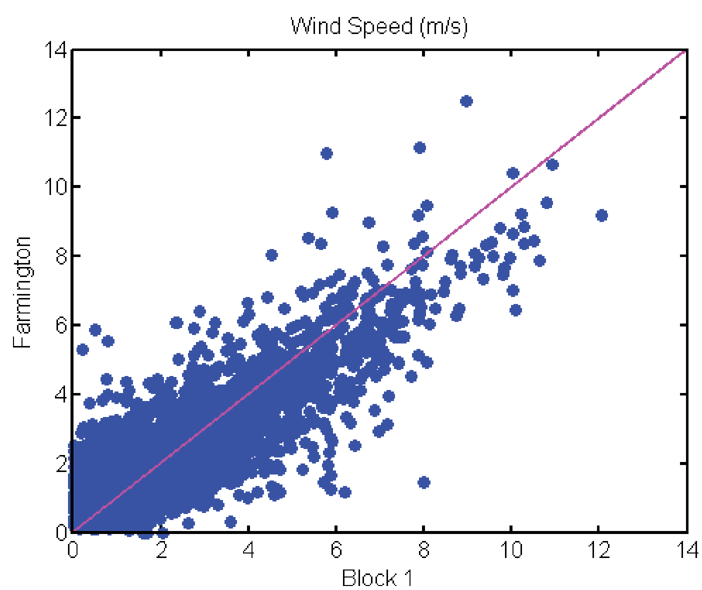
DOY 1 to 30, 2015

Farmington vs Block 1 Meteorological Data – RH Times Series



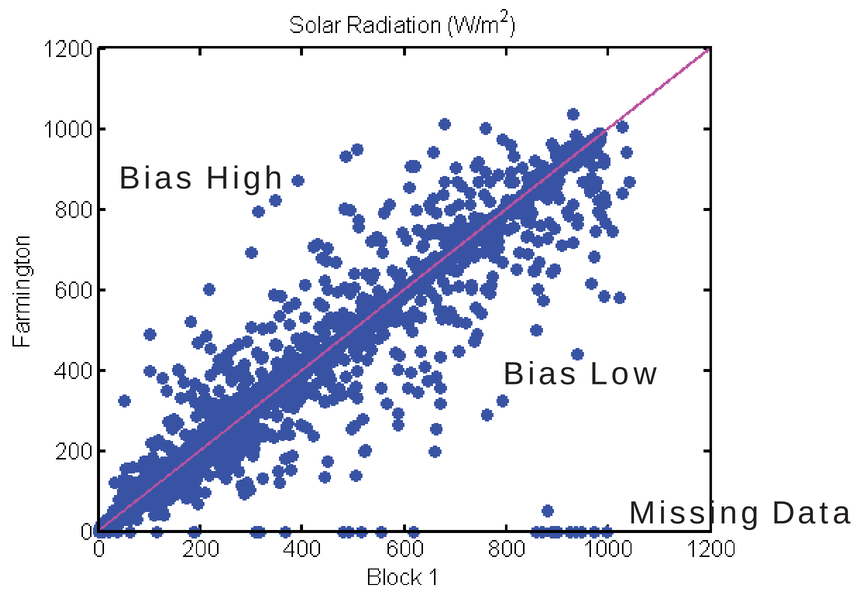
DOY 180 to 210, 2015

Farmington vs Block 1 Meteorological Data – Hourly Wind Speed



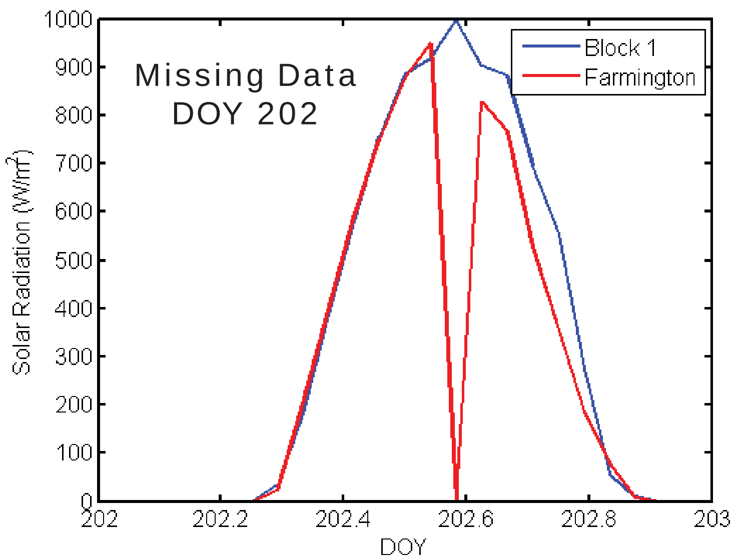
Remote Sensing of Actual ET

Farmington vs Block 1 Meteorological Data – Solar Radiation



Remote Sensing of Actual ET

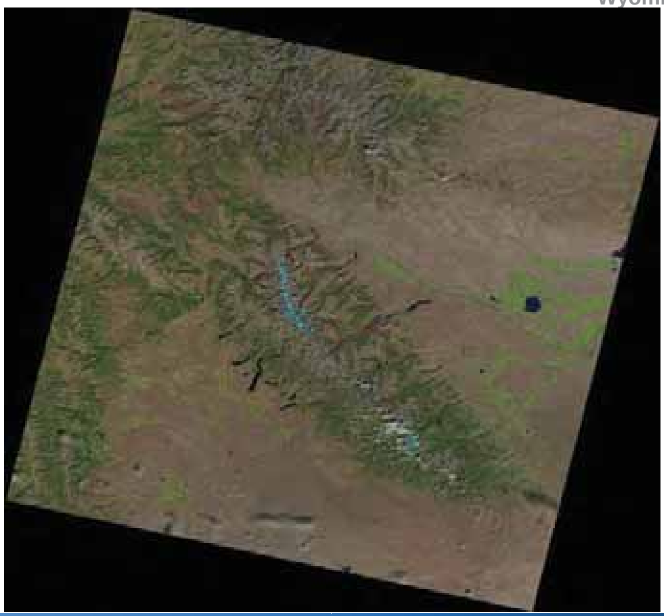
Farmington vs Block 1 Meteorological Data – Solar Radiation



Remote Sensing of Actual ET

Landsat 7 – SLC Failure

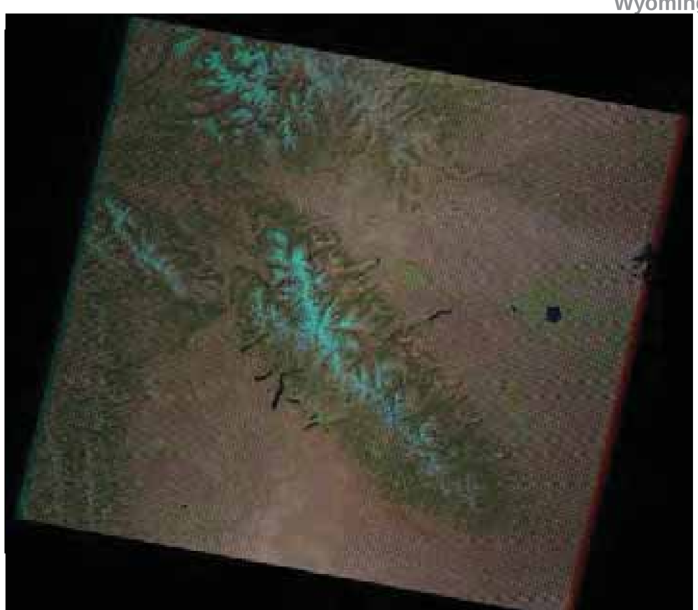
LC803703022015271LGN00
Wyoming



Remote Sensing of Actual ET

Landsat 7 – SLC Failure

LE70370302015263EDC00
Wyoming

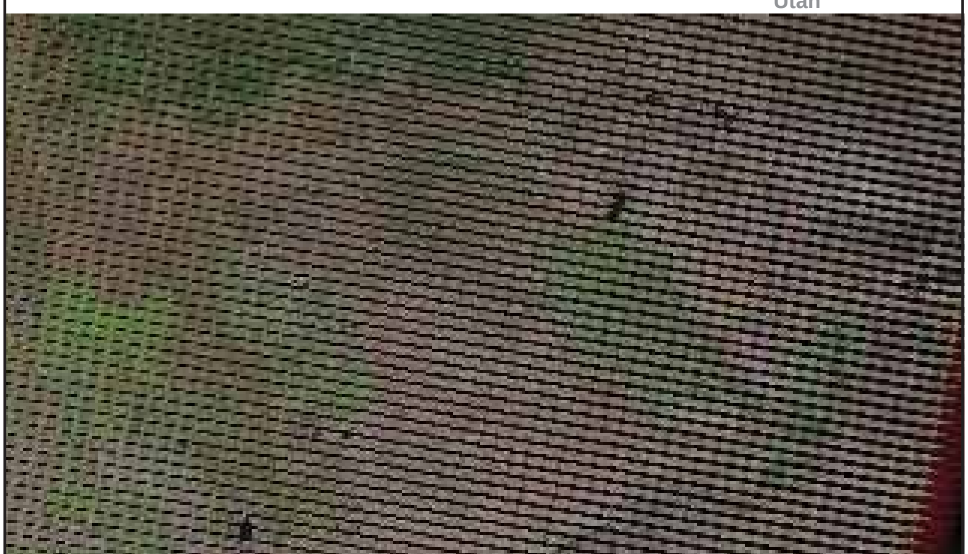


Landsat 7 – SLC Failure

LE70370322015263EDC00
Utah

Landsat 7 – SLC Failure

LE70370322015263EDC00
Utah



Remote Sensing of Actual ET

Shape Files at Edge of Scenes

Path/Row 035/035
New Mexico

Remote Sensing of Actual ET

Shape Files at Edge of Scenes

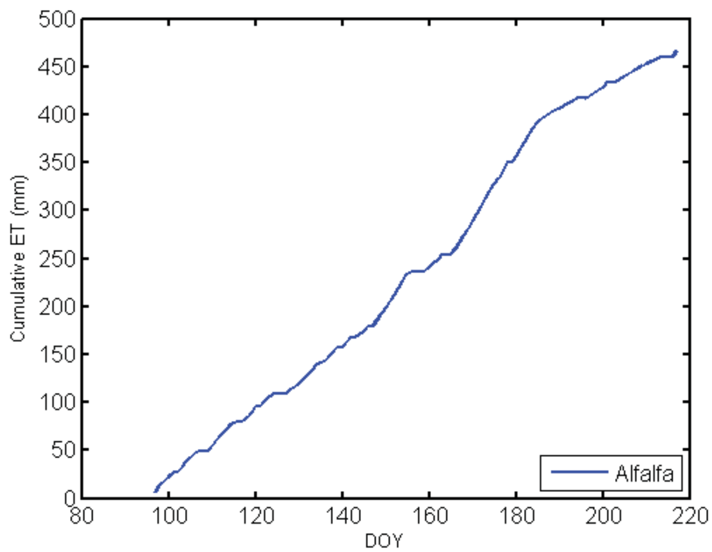
Path/Row 035/035
New Mexico

Shape Files for Crops

Path/Row 035/035
New Mexico

Cumulative Water Use: Alfalfa (partial season)

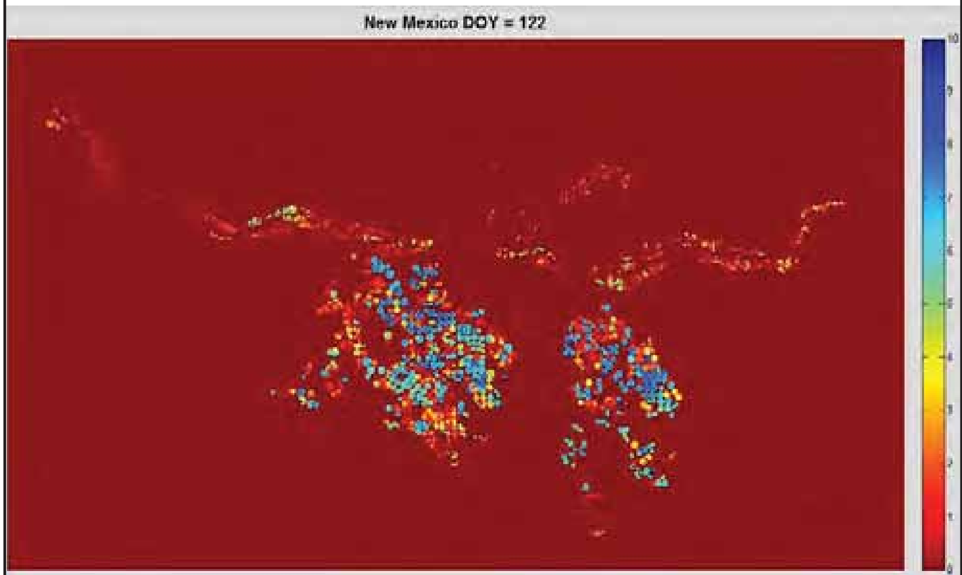
Path/Row 035/035
New Mexico



Remote Sensing of Actual ET

Daily ET Animation (partial season)

Path/Row 035/035
New Mexico

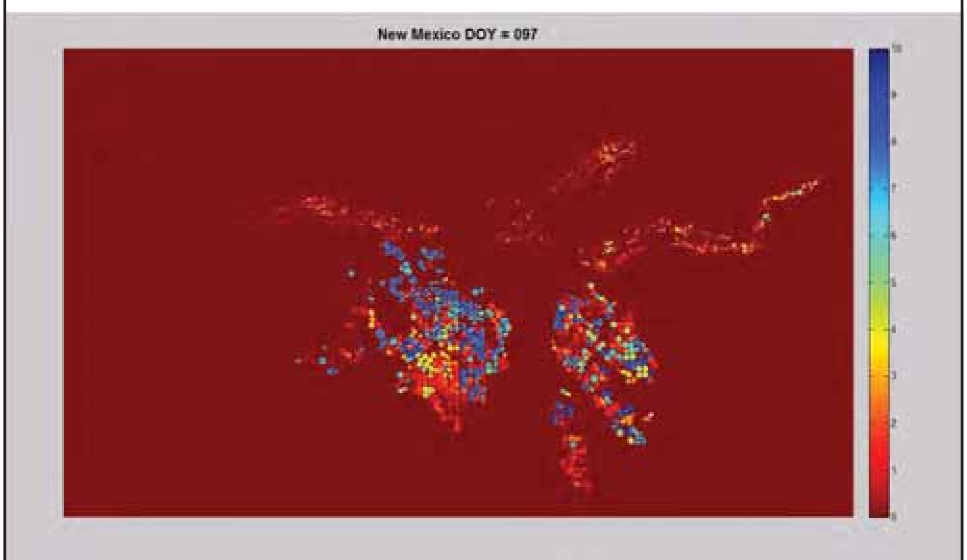


Crop ET **(mm/d)**

Remote Sensing of Actual ET

Daily ET Animation (partial season)

Path/Row 035/035
New Mexico



Crop ET **(mm/d)**

Remote Sensing of Actual ET

Issues "Resolved" 28 Sep 2015

1) Saturation is incorrect

There was a bug in LEDAPS (Landsat SR for 4/5/7) where we were flagging saturation at 16,000, but now we've changed it so it's only 20,000. This should make a difference in what is flagged and what isn't.

2) CFmask shadows

CFmask predicts the cloud shadow based upon spectral response (i.e. proximity of a dark object near a cloud), but primarily relies upon estimating cloud height. There was a bug in CFmask where the cloud height was not being selected correctly from the iterated list of heights. This has now been fixed.
It was reported by other users that cloud shadow was ~50% accurate (we found ~55%), so this number should increase. We are working on getting the new accuracy value for that now.

3) OLI albedo coefficients

Actually, a member of the Landsat Science Team, Prof. Crystal Schaaf from UMB, talked about this in July's meeting. She provided the narrow to broadband coefficients on slide 6 of http://landsat.usgs.gov/documents/science_LST_july2015/SchaafLandsatTMSiouxFallsJuly2015.pdf. I hope that helps.

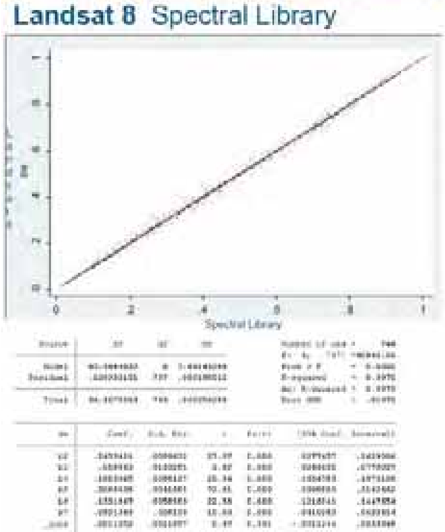
My recommendation would be to re-generate the scenes through ESPA and see if they see improvements.

More info about #1 and #2 is available under the "News Archive" on http://landsat.usgs.gov/CDR_ECV.php (September 28, 2015).

Remote Sensing of Actual ET

3) OLI Albedo Coefficients: Crystal Schaaf, U Mass - Boston

Narrow to Broadband Coefficients – Landsat 8 Spectral Library



Band	Coefficient
B2	0.245342
B3	0.050843
B4	0.180395
B5	0.308064
B6	0.133185
B7	0.052135
Constant	0.0011052

R2 = 0.9970
RMSE- 0.01373

*Currently under validation

Remote Sensing of Actual ET

Draft Project Report Outline

Draft Outline: UCRBC Remote Sensing Report¶

¶

Revised: 04 Oct 2015¶

¶

¶

1. Executive Summary¶
2. Project Objectives¶
3. Brief Description of Remote Sensing Methods (approximately one-half page per method plus a table comparing all methods)¶
   a. R-METRIC¶
   b. R-ReSET¶
   c. SSEBop¶
   d. ALEXI/DisALEXI¶
4. Operational Requirements for Each Method (e.g. computer hardware, software, storage requirements, approximate processing time per scene)¶
   a. R-METRIC¶
   b. R-ReSET¶
   c. SSEBop¶
   d. ALEXI/DisALEXI¶

Remote Sensing of Actual ET

Draft Project Report Outline

5. Operational Difficulties¶
   a. Cloud cover¶
   b. Missing meteorological data and QC of meteorological data¶
   c. Interpolating between days of satellite overpass¶
   d. SLC failure for Landsat 7 data¶
   e. Effects of field cutting with immediate decrease in ET (seen by tower) between days of satellite overpass¶
   f. Shape files at edges of scenes¶
6. Comparison of ET Estimates with Colorado Eddy Covariance Tower¶
   a. Description of tower location and operation¶
   b. Uncertainty in eddy covariance measurements – Closure of the energy balance¶
   c. Description of tower footprint analysis¶
   d. Sources and magnitudes of uncertainty in remote sensing estimates. Random versus bias error. ¶
   e. Results for each method – Cumulative remote sensing footprint ET vs tower ET. RMSE of daily ET. Coefficient of determination of daily ET. ¶

Draft Project Report Outline

7. Comparison of Fully Irrigated NIIT Project Area Penman-Monteith Estimates in NM with Remote Sensing Estimates: Cumulative ET, RMSE and coefficient of determination (or R^2) for daily ET.¶
    a. R-METRIC¶
    b. R_ReSET¶
    c. SSEBop¶
8. Comparison of Cumulative ET for Irrigated Lands by State for Each Method¶
    a. Description of method to compute cumulative ET volume by state¶
    b. Results for each state¶
    c. Information derived from ensemble means for each state¶
9. Discussion and Conclusions¶
    a. Practicality of application of remote sensing methods for evaluation of ET in the Upper Colorado Basin States¶
    b. Operational requirements – Equipment, personnel, time¶
    c. Positives and negatives of each method in an operational mode¶

Draft Project Report Outline

10. Appendix I – Description of Remote Sensing Methods (up to 2 or 3 pages per method, as needed)¶
    a. R-METRIC¶
    b. R-ReSET¶
    c. SSEBop¶
    d. ALEXI/DisALEXI¶
11. Appendix II – Calculation of evaluation metrics¶
    a. Daily RMSE calculation for EC tower comparison¶
    b. Coefficient of determination (or R^2) for remote sensing measurements versus EC tower fluxes¶
    c. Bias calculation¶

Remote Sensing of Actual ET

NASA AirMOSS P-Band Radar Mission

Richard Cuenca p. 41 Hydrologic Engineering, Inc. - 2015

Remote Sensing of Actual ET

NASA AirMOSS P-Band Radar Mission: "Business Class"

Richard Cuenca p. 42 Hydrologic Engineering, Inc. - 2015

Remote Sensing of Actual ET

NASA AirMOSS P-Band Radar Mission

Remote Sensing of Actual ET

NASA AirMOSS P-Band Radar Mission

NASA AirMOSS P-Band Radar Mission

NASA AirMOSS P-Band Radar Mission

CONFERENCE CALL NOTES
Review of Preliminary Memorandum of Agreements for the Upper Colorado River Basin
October 19, 2015, 4:00 p.m. Mountain

Call Participants:
Brenna Mefford, Wyoming
David Merritt, AECOM
Don Ostler, Upper Colorado River Commission
Greg Gates, CH2M
Jody Glennon, AECOM
Kara Sobieski, Wilson Water
Kevin Flanigan, New Mexico
Kib Jacobsen, Bureau of Reclamation
Mike Sullivan, Colorado
Robert King, Utah
Steve Wolff, Wyoming

INTRODUCTIONS
David Merritt started the conference call by reading through the roster of call participants. He then turned the call to Steve Wolff to discuss the first agreement and his thoughts on it.

MEMORANDUM OF AGREEMENT (MOA), CONCERNING THE UPPER COLORADO RIVER BASIN (UCRB) AND THE DEVELOPMENT OF A METEOROLOGICAL NETWORK
Steve plans to sit down with his attorney this week to get Wyoming's thoughts on paper. Steve feels additional specifics are needed in regards to how the States and the Bureau of Reclamation commit funds and resources via this MOA. The MOA needs to address the challenges with new versus existing stations, and specifically state how MOA money can and cannot be used.

Don Ostler stated that the Commissioners have basically approved $500K for "in and on the ground expenditures" that somewhat cover the first year of operations and maintenance (O&M), though that still needs to be verified. Don feels the team would be considered negligent if a valid plan that details the responsibility and commitments by the States and the Bureau of Reclamation is not developed for continuing O&M support after year one for the existing and new stations. Don stated the team has a moral obligation to keep operating the stations.

Steve also expressed that the MOA needs to cover annual team communications and updates for each station, and that issues need to be raised early so that there is ample opportunity for resolution each year.

Steve plans to draft language regarding how MOA funds can and cannot be used. He requested that Kib Jacobsen review that verbiage with Bureau of Reclamation legal staff and provide edits/comments as appropriate. Kib agreed.

David iterated that the team needs to move this MOA along quickly so that it can be finalized and signatures can be obtained soon. David asked if the states were comfortable with that direction and the State representatives responded favorably. David then turned the focus of the call to the mid/longer term MOA.

MOA, CONCERNING THE REPORTING OF CONSUMPTIVE USES AND LOSSES IN THE UCRB
Steve expressed that although he still needs to review this MOA in its entirety, he has already identified some changes and modified verbiage that are needed and plans to go through the MOA carefully.

David expressed that the team needs to lay a set of tracks for those that follow relative to computations and coordination.

NEXT STEPS
Steve plans to release his revised version of the MOA Concerning the UCRB and the Development of a Meteorological Network to the call team by close of business (COB) this Friday, October 23, 2015. The team should review that version (in place of the version provided to the team on October 12, 2015) with their respective legal representatives and provide track change/red-line edits and comments to David by COB Thursday, November 5, 2015.

The team should also review the MOA Concerning the Reporting of Consumptive Uses and Losses in the UCRB (the version released on October 12, 2015) with their respective legal representatives, and provide track change/red-line edits and comments to David by COB Thursday, November 5, 2015.

David will release revised versions of both MOAs to the call team by COB November 6th. On Monday, November 9, 2015, at 10 a.m. Mountain, a follow-on call will be held so that both MOAs can be advanced in preparation for the Principal's Meeting being held in Albuquerque, New Mexico on December 2, 2015.

CONFERENCE CALL NOTES
Review of Draft Memorandums of Understanding for the Upper Colorado River Basin
November 16, 2015, 2:00 p.m. Mountain

Call Participants:
Brenna Mefford, Wyoming
Don Ostler, Upper Colorado River Commission
Erin Wilson, Wilson Water
Greg Gates, CH2M
Jim Prairie, Bureau of Reclamation
Jody Glennon, AECOM
John Longworth, New Mexico
Kevin Flanigan, New Mexico
Kib Jacobsen, Bureau of Reclamation
Michelle Garrison, Colorado
Mike Sullivan, Colorado
Steve Wolff, Wyoming

INTRODUCTIONS
Don kicked off the call and stated the purpose of the call was to further the Memorandum of Understanding (MOU) Concerning the Upper Colorado River Basin (UCRB) and the Development of a Climate Station Network, and the MOU Concerning the Reporting of Consumptive Uses and Losses in the UCRB in conjunction with the Draft Phase II Report that is being presented to the Upper Colorado River Commission (UCRC) on December 2, 2015. The goal is to get the MOU Concerning the UCRB and the Development of a Climate Station Network to a point that recommendations can be made at the meeting on December 2nd, and to take the other MOA as far as possible so that it also can be presented and considered at that meeting.

MOU CONCERNING THE UCRB AND THE DEVELOPMENT OF A CLIMATE STATION NETWORK
Steve walked the call team through his primary changes to this MOU, which included developing a bulleted list of responsibilities for the States, Bureau of Reclamation (Reclamation), and the UCRC under Section IV, Purposes.

Don indicated Steve had gotten this MOU closer to what the UCRC would want, which is specificity.

Kevin expressed some concerns from New Mexico about their ability to cover operation and maintenance (O&M) costs. New Mexico currently does not have funding or resources for this.

Steve indicated David Dubois had said if funding was available, he would be able to maintain stations not on Navajo land. Erin confirmed her same understanding and added that David may be able to maintain Navajo stations, too, if funding makes that possible. However, without funding, David cannot help. Don stressed that the MOU indicates if states *can*, they will cover O&M expenses.

Erin confirmed the Aztec Station is not on Navajo land.

It was stated that long-term agreements rely on legislative funding. Mike indicated for Colorado, a legislative fix is required, so Colorado is likely a year and a half out before they can ensure O&M funding.

Don believes some MOU funds can be used to fund O&M. Mike reminded everyone that they are in a Tabor year, so funding mechanisms can become a bit strange. Erin confirmed with Mike that Colorado is behind the project and supportive of pushing it and actively looking for funding.

Kib said MOU funding would have to be used for federal stations. Don said new stations would be purchased with MOU money and be federally owned. Kib confirmed. Such funding would cover the Table 2/new stations. Erin reminded the callers that money reflected in the tables included some training and maintenance funds.

Erin plans to circle back with David Dubois to check status. For the future O&M money from Reclamation that goes towards new stations, under Section V, Steve's intent was to leave that 20 percent somewhat flexible so it could be directed where it was most needed. State/UCRC/Reclamation would decide where that funding could be used each year. Erin indicated she thought that made a lot of sense; however, having that funding available in the short-term could be very helpful as the states go through their legislative processes.

Don reminded the team that the costs for the Eddy Covariance Towers are still pending. Depending on the Eddy Covariance Tower costs, Don indicated money may remain for those under the initial authorization for the annual O&M costs if the UCRC deems to approve that money for ongoing O&M.

Steve asked if Kib could provide costs. Don said him and Jim could work with Kib to determine those. Steve suggested waiting until the team knows if they are proceeding with remote sensing as the number and locations could change based on selection of remote sensing/ground truthing/etc. O&M costs for the Eddy Covariance Towers are more than those for the Climate Stations. *Erin will check with Chad Higgins to confirm he plans to include updated costs in his Phase II report piece.* His Phase I estimates indicated $60K total for O&M and $40K per station installation. Brenna discussed that data analysis costs should be coming down due to the new Eddy Covariance data technology that is available. Costs for one versus three are about the same for O&M. $200K is likely what the team is looking at.

Don inquired if a pilot study was deemed appropriate, if the Eddy Covariance Towers would be needed. Steve responded yes, but only one (i.e., not all four).

Requests need to be submitted late spring/early summer for 2018 reserves.

Steve requested that the team look at the state recitals up front in the MOU and get back to him with their updates this week. Steve will then incorporate those updates and attempt to massage the language New Mexico expressed concern about.

For the upcoming workshop, Erin suggested 10-15 minutes for this piece. This draft MOU should be provided to the Commissioners before the 12/2 meeting. Steve suggested a few days ahead of time and before Thanksgiving. *It was decided that Steve would send the MOU to Deon to forward to the Commissioners.*

Erin indicated Chad Higgins and Richard Cuenca have been working hard on their presentations and are trying to get those to Erin mid-week next week for her review and feedback regarding the appropriateness of the level of detail.

MOU CONCERNING THE REPORTING OF CONSUMPTIVE USES AND LOSSES IN THE UCRB

Jim led the discussion of this MOU. Jim indicated his revisions were an attempt to build a picture of the near-/mid-/long-term, and indicated he left the recitals and purpose sections alone. Mike had provided some edits to Jim. Jim clarified that he modified the timing discussion so as not to reflect 10 years to accomplish the project. In the near-term, the plan would be to continue to evaluate methods for potential and actual ET in the first 2-3 years and build the data sets. In the mid-term, the focus would be on finalizing the evaluations done under the near-term. And the long-term would involve implementing what gets recommended.

Kib requested that the O&M discussion be expanded to specify the authority. Jim agreed and indicated he would incorporate language modifications to reflect that.

Don expressed a concern about this MOU being very consumptive uses and losses (CU&L) report oriented whereas the intent is to get good numbers that the Commissioners can use. *It was agreed that CU&L spell outs in the MOU would be lower case. Kib further suggested softening the CU&L language and carrying that throughout the purposes section of the MOU. Jim plans to address these suggestions.*

Steve had to depart the call at this point due to another call commitment. *Steve expressed that he has edits to this MOU and would forward those to Jim and Jody.*

Mike had comments on the definitions listed in this MOU, specifically Current Conditions. *Jim plans to revise the definition for Current Conditions to include Wyoming's current methods and then not use that terminology later in the MOU to avoid confusion.*

The team indicated support of Jim's revised timeline definitions for near-, mid-, and long-term and agreed he should carry those forward.

Jim then walked the team through the Agreements Section. Mike specified that Policy and Legal will not be informed by the results of the study and that the MOU needs to reflect clearly that actions 1-5 will be done concurrently (to the extent possible since some of the actions inform other actions) versus sequentially (i.e., they will all be looked at together). *Jim agreed and plans to add language to indicate there is no action priority relative to those.*

Mike suggested adding language to a cover letter (short, one-page synopsis type letter) about the Eddy Covariance Towers to remind the Commissioners that those are not covered under this MOU. Don liked that suggestion as a means to keep the towers on the Commissioner's radar due to the large dollar investment associated with those. Ultimately, a future agreement for the Eddy Covariance Tower installations and maintenance will likely be required.

Jim asked that the call team forward their additional edits comments to him to incorporate. Don confirmed that Jim has not heard anything from Robert/Utah; Don plans to reach out to Robert.

Don asked if Reclamation was still okay with things based on today's discussion; Kib indicated he felt the team was headed in a good direction.

Jody noted that MOU versus MOA (Memorandum of Agreement) terminology was being used interchangeably. It was agreed that MOU should be used for both of the memorandums discussed today, both in their title and content within. Jody and David previously standardized that in the MOU Steve is leading and *Jim plans to standardize that in this MOU.*

Jim plans to address the edits/comments received and to release a revised MOU on November 18th. Comments on that iteration are requested by COB November 20th. From there, Jim will release a draft version to Don to forward to the Commissioners by November 25th.

NEXT STEPS
Please see italicized text for assigned action and follow-up items.

CONFERENCE CALL NOTES
Preparation for December 2, 2015 Meeting with the Upper Colorado River Commission
November 30, 2015, 3:00 p.m. Mountain

Call Participants:
Chad Higgins, Hydrologic Engineering, Inc. (HEI)
Dave Eckhardt, Bureau of Reclamation (Reclamation)
David Merritt, AECOM
Don Ostler, Upper Colorado River Commission (UCRC)
Erin Wilson, Wilson Water
Jim Prairie, Reclamation
Jody Glennon, AECOM
Kib Jacobsen, Reclamation

OVERVIEW
David started the conference call and announced the list of call participants. He then requested that Chad provide an overview of Dr. Richard Cuenca's remote sensing assessment for the project.

Chad indicated he had a lot to show from Richard; Chad and others coordinated and now have the cumulative evapotranspiration (ET) for each State complete. What remains/is not complete is the assessment of all possible methods.

For Colorado, four methods (i.e., R-METRIC, SSEBop manual, SSEBop automatic, and SSEBop cold pixel) were assessed for measuring cumulative ET, and the results are comparable, in a gross sense, to the results of the Eddy Covariance (EC) technique. A more specific comparison is forthcoming.

Jim indicated that what is missing from the assessment for Colorado at this time is R-ReSET and ALEXI/DisALEXI. For the other states, Chad indicated only R-METRIC and SSEBop results are available.

Chad indicated the difference in results between the methods is to the tune of 20 centimeters (cm) cumulative ET per year (top to bottom). The SSEBop manual and automatic provide very close results to the EC Tower data.

Chad stated he has multiple seams to show as visual aids at the presentation. Chad's analysis of the EC data is available and he plans to present the cumulative only results at the meeting so as not to overwhelm the audience with data. The call team concurred that was a good approach.

Relative to the EC Tower data, there appears to be roughly 40 percent error with the remote sensing methods. Don expressed concern that such fluctuations indicate none of the remote sending methods are precise. Chad reminded the call team that only one season of data is available, so at this time, he is not able to determine variability. Jim stated that Gabrielle is the U.S. Geological Survey (USGS) Lead and can indicate whether a plus or minus of error is available. Jim indicated he would forward Chad Gabrielle's contact information.

Don requested that the call team discuss recommendations/the outlook for next steps. Jim thought the recommendation would be to do the study on a larger scale with additional EC Towers. Chad also recommended continuous monitoring and continuous improvement. Don expressed concerned about the potential reaction from the Commissioners to such recommendations – could appear as a never-ending study with a large cost.

Chad is unaware of Dr. Cuenca's percent completion with the R-ReSET method. The SSEBop automatic did provide slightly worse results than SSEBop manual…SSEBop manual is the winner, and SSEBop automatic comes in second. There is a price differential between these two methodologies – the automatic method is scriptable whereas the manual requires man hours to operate.

Chad indicated he does have enough information to do a cost analysis to run those analyses and will do so based on hours and pay rates. Don requested a ballpark of costs. Chad quickly scanned the data…he estimated a half hour per seam; 20 seams per this growing season; and cited an experienced user. For four seams per year, he estimated two to four person months per year, at $100 per hour, or $10K-$15K per year, per state. Sixteen seams would cover the four States and equate to one full-time job. Jim inquired if the methodology selected would impact this calculation – Chad clarified that the automatic methodology would be cheaper (probably half the cost of the manual).

Chad asked what the next highest priority item for the team was for the presentation. The call team could not think of anything. Chad confirmed the EC Tower plot and the Colorado plot would be presented side-by-side at the meeting on December 2nd.

Chad confirmed the pilot EC Tower is located in Silt, Colorado, near Divide Creek. Chad indicated the satellite data for Utah is complete but there is not a lot of relationship between the EC Tower data and the Utah data.

Chad recommended the SSEBop be rolled out over a larger area, preferably the enter Upper Colorado River Basin, and that one or more locations be added to check those results (i.e., at least one more EC Tower, if not more, depending on how the States wish to invest). The EC Towers could then go away in the future if confidence is built in the satellite methods.

Don inquired about the advantages/disadvantages of the different calculations. The Blaney-Criddle method is still being used and the Penman Monteith method is being expanded. Chad indicated he would discuss the strengths and weaknesses of those methods relative to the EC technique and satellite technique, and the relative potential errors of each, at the meeting. Don stressed it was important to give the Commissioners a feel for whether remote sensing will provide more accurate estimates in the future. Chad said remote sensing would provide "a more complete estimate." The satellite method provides every field. Climate station networks have to be transferred and translated from a single place to many – this introduces errors when the data is aggregated.

Advantages of the satellite technique include not having to actually go on the land; maintenance of less infrastructure; and no translational errors. Going from potential ET to actual ET is where translation occurs. Don said there are still several questions to resolve in going from potential to actual ET. Chad indicated the EC Tower has far less assumptions and is entirely independent of the other methods; additionally, the EC Technique has been the standard for measuring flux the past 20 years.

Remote sensing may provide economies of scale; could be manned by one person covering the entire Upper Colorado River Basin. Erin indicated the climate network helps establish an understanding of potential consumptive use and shortages. Generally, one full-time person operates the climate stations in Colorado; for the other States, it is a part-time job.

Don requested that Chad be prepared to discuss the number of EC Towers being recommended and the compromise between total coverage and economies of scale. Chad responded that different strategies are available depending on philosophy (i.e., whether the intent of the EC Tower is just to validate satellite data versus to serve a purpose with the climate network). If the philosophy is that the EC Tower is just to validate satellite data, Chad recommended placing them in places where there is overlap. If there is a competing desire, Chad recommended placing the EC Towers near climate stations. There are tradeoffs with both philosophies. The cost of moving an EC Tower is estimated at $16K; the team would need to gain a lot from moving an EC Tower and Chad does not see the worth.

Chad is planning for 20 minutes for his discussion at the meeting and will allow time for questions/comments. Erin estimates her part to be 10 minutes as she will not be presenting anything new. Jim estimates his required time as 10 minutes, too, as he plans to provide a broad overview of the Memorandums of Understanding (MOUs) that have been drafted. The team understands Steve also plans a brief presentation – a briefing. Don believes the Commissioners will request time to review the report. He plans to hold on providing paper copies until Dr. Cuenca's remote sensing piece is in the report, but will provide an electronic copy of the report to the Commissioners either before or after the meeting.

Chad indicated Dr. Cuenca will be doing rehab in Sonoma, California, after he gets released from the hospital.

Don is hopeful that the Commissioners will concur with moving forward following their reviews of the MOUs. A remote sensing decision will follow completion of the final report. The current report contains preliminary recommendations that can be discussed at the meeting. Don hopes by June the team can bring a definitive plan to Commission. Erin stressed that Chad's report piece includes first and second choice EC Tower locations for each State.

David inquired as to the status of the Lower Colorado River Basin effort. Jim indicated that team has developed new consumptive uses and losses and their timeline is to get the new computations done by 2017. The States are going to want to compare what have they have been computing to the remote sensing results. Erin indicated she could do that comparison in about an hour. Wyoming has done some comparisons, and Colorado has also (on the East Slope), so some estimates have been made.

Dave confirmed the final report completion depends on Dr. Cuenca's recovery.

CONFERENCE CALL NOTES
UCRC CU/LOSSES TECHNICAL STEERING COMMITTEE
23 FEBRUARY 2016
10:00 A.M. - NOON
CONFERENCE CALL
888-369-1427 PIN 3844738

Meeting Participants:
Brenna Mefford, Wyoming
Dr. Chad Higgins, Hydrologic Engineering, Inc.
David Eckhardt, Bureau of Reclamation
David Merritt, AECOM
Don Ostler, Upper Colorado River Commission
Erin Wilson, Wilson Water
Gabriel Senay, USGS
Jim Prairie, Bureau of Reclamation
Jim Verdin, USGS
Kara Sobieski, Wilson Water
Kevin Flanigan, New Mexico
Kib Jacobsen, Bureau of Reclamation
Michelle Garrison, Colorado
Mike Sullivan, Colorado
Dr. Richard Cuenca, Hydrologic Engineering, Inc.
Robert King, Utah
Steve Wolff, Wyoming

Remote Sensing Update – Draft Remote Sensing Recommendations

- **Discussion of Model Comparisons** — **Dr. Richard Cuenca**
- **Discussion of Operation Needs** — **Drs. Cuenca & Higgins**
- **Potential Number of Towers Needed** — **Dr. Chad Higgins**
- **Where to Install Towers** — **Drs. Cuenca & Higgins**

Dr. Cuenca and Dr. Higgins discussed the draft remote sensing analysis results and recommendations as provided in the *Report and Recommendations on Remote Sensing (Ver 2).pptx* and *Remote Sensing Executive summary USBR (Ver 6).docx*. The discussion began with a review of Figure 1 from the Executive Summary, noting that the top black line in the figure represented the Penman-Monteith reference evapotranspiration (ET) cumulative value, whereas the other methods presented in the graph reflected water supply limited estimates of actual consumptive ET. The SSEBop:HEI Cold Pixel values (yellow line) was developed by Dave Eckhardt based on a 1.05 value of the ET for cold pixels. Dave ran a few other options with SSEBop using different pixel options and will provide those results in future reports. It was noted that the cumulative ET values for the Colorado site in the presentation differed from those presented in the Executive Summary. Dr. Cuenca and Dr. Higgins noted that this was due to using an interpolation method for the presentation graphs to fill the data gap in the tower data near DOY 190; they recommended using this interpolation method in the final report.

Dr. Cuenca and Dr. Higgins re-emphasized that the data gap in the tower data was caused by a memory card overload and that use of CR6 dataloggers in the future will correct this issue. It, of course, doesn't preclude other issues with the tower occurring in the future though.

There was discussion between Dr. Cuenca, Dr. Higgins, and Dave Eckhardt regarding the fact that the ET results from this tower reflect only one data point in Colorado and the Upper Colorado River Basin (UCRB), and that the remote sensing results have not been ground-truthed or compared to results for any sites with variations in environment, elevation, or water supply. Dave noted that there are several different remote sensing methods that generally rely on the same kinds of satellite data but leverage this data differently to develop reference ET values. All of these methods can "get you in the ballpark" for reference ET data, but on-the-ground data from towers, met stations, or other actual ET methods are necessary to constrain and/or bound the satellite estimates. With this in mind, users can then compare costs of different remote sensing options, including the option of some automation of data processing.

Additional points from the Executive Summary were discussed, including Dr. Cuenca's and Dr. Higgin's recommendation to install a more extensive Eddy Co-variance (EC) Tower Network; ideally at least one tower in each state. This would allow the remote sensing results to be ground-truthed to results from towers in a more representative environment and/or elevation. Additionally, they noted that all the methods presented in Figure 1 had similar seasonal patterns and were constrained by water stress as compared to the Penman-Monteith method. In general, they felt that once ground-truthed, the remote sensing results provided a pretty good estimate of actual ET and really only lysimeter results would be more exact. They noted that the remote sensing effort could be implemented for the entire UCRB as is; however, tower site in each state would provide more confidence of the results throughout the basin.

Don Ostler recalled a comparison of ET results from remote sensing to other empirical methods in the Upper Basin. Jim Prairie and Dave Eckhardt noted this was a comparison performed by Bureau of Reclamation (Reclamation) at two sites: Palo Verde Irrigation District (PVID) in Arizona and Mead, Nebraska. For the PVID site, both Utah State and Reclamation performed water balances; Reclamation included an estimate of non-measured return flows and Utah State did not. The Utah analysis results most closely correlated with METRIC results and the Reclamation analysis results most closely matched the SSEBop method results. For the Mead, Nebraska site, METRIC provided an over-estimate while SSEBop results were much closer to the empirical method results. The final report for this effort has not been published; however, Dave has the latest draft.

Dr. Cuenca noted another comparison for a NASA study that included three wooded/grassland (non-irrigated) sites in California and Oregon. In this study, METRIC results correlated fairly well at sites with low ET, but over-estimated ET at sites with more moderate ET.

Don Ostler requested that a comparison of these results to existing methods used for the Consumptive Uses and Losses reporting in the UCRB, including Blaney-Criddle and the indicator gage method, also be made for the tower site in Silt. Erin Wilson indicated that this comparison effort was removed from the scope, but that the comparison could be made. Dave Eckhardt indicated a concern over capturing the impact of cutting and not replanting in the Blaney-Criddle analysis, and Erin indicated that diversion records will capture that. The group noted that the ultimate question is whether the new method is better.

Jim Prairie discussed the on-going Reclamation (Alan Harrison) comparison effort for the entire UCRB area that looks at how Penman-Monteith results compared to Blaney-Criddle results on a monthly time-step, both limited by the indicator gage method. There is no solid date for a published report; email Jim Prairie for more information on this effort.

There was some confusion on the estimated time to analyze slides. Dr. Higgins clarified that the time estimates in the presentation were based on approximately 18 scenes representing the entire UCRB area, and they were revised from the original report after discussing the level of effort with technicians and accounting for some contingency. It was noted that speed depends on experience and that significant time was spent on homogenizing and QAing/QCing the MET data for each of the scenes. Jama Hamal provided some of that effort for the Utah and Colorado scenes for this effort. The time estimate, 0.35 full-time equivalents (FTE), reflects the man-hours needed to process data and perform the METRIC analysis; it does not include the SSEBop analysis. Additionally, Dr. Higgins indicated that slide four of the presentation reflected the cost to setup, install, and provide operations and maintenance (OM) on a single tower, including a 20 percent contingency.

Gabriel Senay noted that use of GridMET or METData (from Idaho) provided a good comparison to data used in the SSEBop analysis, and it may save some time and allow for some automation. Dave Eckhardt asked about how quickly the data is available, and they noted that it was available fairly quickly (i.e., two days for some data types) and that the datasets do include reference ET estimates.

Dave Merritt polled the state representatives about how comfortable they are with full basin implementation of METRIC. Steve Wolff indicated that they really need a final report to look at the results before they could discuss full basin implementation; Dr. Cuenca indicated the final report would be available by the end of the month.

Don Ostler brought up the question as to the usefulness of the towers if the states did not move forward with a remote-sensing option. Dr. Cuenca and the state representatives indicated that the towers can still be used for ground-truthing any method, and there is value to maintaining towers even without remote sensing options. Don Ostler indicated the states will need to discuss if they would like one tower per state, how to pay for that tower (including potential use of some Memorandum of Agreement [MOA] funding) and if renting equipment is an option. Dr. Higgins indicated that the EC Tower Report is finalized and will be included in the upcoming Final Phase II Report. It includes potential tower sites; Erin Wilson asked if the sites reflected variable water supply conditions and Dr. Higgins indicated they do not. Dr. Higgins indicated that he could include these criteria in tower siting options if Erin Wilson could provide input (or GIS layer) with this information.

Dave Eckhardt presented an idea for a "Super Ground Truth Dataset" which would ideally include 100 fields with daily diversion records, ample water supply, known crops, and known irrigation practices (potentially GVIC or Uncompaghre Valley). This dataset could be analyzed with a Penman Monteith method and could be useful for comparisons.

Climate Station Update – Installation and operational issues.

- Station installation schedule.
- Equipment list needs from each state.
- Is there a need for any additional agreements.
- Calibration documentation by each state.
  - Agree to annual calibration. Document calibration each year and make log available to the public. How can we do this?
- QA/QC documentation by each state. Universal document on methods. Every state will follow the ASCE Standards; protocol may vary by State.
- Means to serve the QA/QC data are in placed by the next growing season (2017).
- MOA authorization and where we are with those funds.
- Need to add extra funding for state involvement in station siting (1 or 2 days for NM, 2 weeks for CO, 3-5 days for UT).
- Reclamation will pay for all station installation and operation for first year.

Erin Wilson and Kib Jacobsen presented the change in funding scenario for the climate network. Originally, Reclamation was going to cover 20 percent of the first-year costs and 20 percent of subsequent year OM. Reclamation received some additional funding and proposed covering the whole first year cost ($176,000) for climate stations in CO, UT, and NM. The states would then need to cover the OM costs, potentially from MOA funding. Wyoming is still okay with not getting funding for their climate station equipment and installation. This change in funding will need to be reflected in the MOU; Steve Wolff will include the revised funding option in the most recent version of the MOU and circulate to the states by Monday. If the states agree to the climate station MOU, Kib indicated that he can provide authorization to Jama Hamel to order the climate stations. Erin indicated that it will take approximately 8 weeks for delivery directly to the states; that they could be installed by the summer; and could provide data for the 2017 irrigation season.

There was significant discussion as to what agreements would need to be in place in order for the States to use MOA funding to perform OM on the climate stations over the next 10 years. Two agreement options were presented:

Option 1:

- Reclamation to transfer MOA funding over to States for station OM
- States to transfer funding over to State Climatologist for station OM
- State Climatologist to landowners regarding the climate station equipment

Option 2:

- Reclamation to transfer MOA funding directly over to State Climatologist for station OM
- State Climatologist to landowners regarding the climate station equipment

Each of the states will need to look into the feasibility of each option and investigate the specifics of the agreement (e.g., Colorado may need to have CWCB and/or SEO involved in agreements; Kevin needs to discuss options with Dave Debois; etc.). These options however would not hold up the climate station MOA as the funding option would not be needed until next year.

As part of the climate station OM, Jama Hamel will set up consistent OM procedures that each state will perform, and then the states sign off on a report that the OM has been completed. She cannot perform the OM for the entire network.

Unfortunately, MOA funding is not currently sent to any of the states, eliminating the possibility of an amendment; new agreements will need to be created. Kib asked Don Ostler if there were sufficient MOA funds to cover the costs for OM for 10 years. Don indicated he needed to develop an MOA accounting summary and present this to the states. From there, the states can decide how to move forward with both approving the use of MOA funding for climate station OM and/or installing new towers if sufficient funds remain. Any expansion of MOA funds can be discussed by the group after the final report is published. Kib reiterated that Reclamation really needs a commitment from the states to cover these OM costs; the group decided that signing the climate station MOU would be sufficient in showing this commitment.

Erin Wilson presented two additional funding requests to the group; Jobie (UT) would like to be reimbursed ($2K-$3K) for citing stations and Jana Hamel would like to purchase two additional sets of climate station equipment to keep on hand for replacements (approximately $15K). Robert King indicated he will coordinate with Jobie on his costs, and Kib indicated additional funds for climate station replacements could be arranged.

Where do we go from here?

- Final Report Phase II
- Phase III
    - Support for MOU implementation
    - Task 4 from Phase II original scope
    - Technical Resource & Coordination role
    - Remote Sensing Implementation for Pilot Study

Dave Merritt moved the discussion to the group's next steps, potentially a Phase III effort. Based on the Phase III efforts summarized in the agenda, Don Ostler asked if the technical consultants could provide an estimate for costs for the group to consider. Dave indicated that the consultants need a specific request from Reclamation for a scope of services which would include an estimate of man-hours for this effort, and lacking that, cannot provide that information. The group does have the cost estimates for additional towers and implementing remote sensing throughout the UCRB to rely on. Don indicated that Reclamation and the states need to review the final report then meet privately to discuss future efforts.

URS

Assessing Agricultural Consumptive Use in the Upper Colorado River Basin – Phase II

AGENDA
UCRC CU/LOSSES TECHNICAL STEERING COMMITTEE
23 FEBRUARY 2016
10:00 AM - NOON
CONFERENCE CALL
888-369-1427 PIN 3844738

Remote Sensing Update – Draft Remote Sensing Recommendations

• **Discussion of Model Comparisons**	**Dr. Richard Cuenca**
• **Discussion of Operations Needs**	**Dr. Cuenca & Higgins**
• **Potential Number of Towers Needed**	**Dr. Chad Higgins**
• **Where to Install Towers**	**Dr. Cuenca & Higgins**

Climate Station Update – Installation and Operational Issues

- Station installation schedule.
- Equipment list needs from each state.
- Is there a need for any additional agreements?
- Calibration documentation by each state.
  - Agree to annual calibration. Document calibration each year and make log available to the public. How can we do this?
- QA/QC documentation by each state. Universal document on methods. Every state will follow the ASCE Standards, protocol may vary by State.
- Means to serve the QA/QC data are in place by the next growing season (2017).
- MOU authorization and where we are with those funds.
- Need to add extra funding for state involvement in Station Siting (1 or 2 days for NM, 2 weeks for CO, 3-5 days for UT).
- USBR will pay for all station installations and operations for first year.

Where to Go From Here

- Final Report Phase II.
- Phase III.
  - Support for MOU implementation.
  - Task 4 from Phase II original scope.
  - Technical resource & coordination role.
  - Remote sensing implementation for pilot study.

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From ASCE-EWRI Task Committee Report, January, 2005

WEATHER STATION SITING

The standardized ET_{ref} equation was developed using meteorological data collected over dense, fully transpiring canopies of grass or alfalfa meeting the definition of the reference surface condition. When possible, meteorological data used for estimation of ET_{ref} should be measured over vegetation that approximates the reference surface. Ideally, weather stations should be centrally located within a large, nearly level expanse of uniform vegetation that is supplied with sufficient water through precipitation and/or irrigation to support ET at or near maximum levels. In an ideal setting, the vegetation extends at least 100 m in all directions from the weather station. However, it is recognized that frequently such a weather station site is not available. The preferred vegetation for the site is clipped grass; alfalfa or a grass-legume pasture maintained at a height of less than 0.5 m may also serve as an effective vegetation for the site. Meteorological measurements made over other short, green, actively transpiring crops will approach reference measurements, provided canopy cover exceeds approximately 70%. A station may be located on the periphery of a field meeting reference conditions provided the station is located downwind of the field during daytime hours.

Weather stations should be isolated from nearby obstacles and obstructions that can impede airflow and/or shade the site. The recommended horizontal separation distance from such obstacles should exceed 10 times the height of the obstacle. Fences used to protect the station from unwanted intrusions by animals should be made of a porous fencing material (e.g., woven wire or chain link); fence height should not extend above the height of the anemometer.

In summary, stations should be:

- In a representative location where at least 70 percent irrigated vegetation is within a 300-foot radius or greater.
- Located not more than 150 feet from irrigated fields.
- Ten times the distance of the tallest object away from the object (example: tree is 50 feet tall, station should be 150 feet from the tree). Some trees on north side of station may be okay – south side, not okay.

From our experience, the best sites are typically on sites where the landowner is enthusiastically supportive and where a pivot corner or line-set field corner location meets the fore mentioned criteria. Also, sites must have cell signal for data telemetry – Verizon carrier is preferred.

UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

PERMIT TO ENTER FOR AGRIMET STATION

AgriMet is the Northwest Cooperative Agricultural Weather Station Network. It is operated by the U.S. Bureau of Reclamation, Pacific Northwest Regional Office, 1150 North Curtis Road, Suite 100, Boise, ID, 83706-1234. Phone: (208) 378-5203.

The undersigned, ____,
hereinafter referred to as Landowner, states as follows:

That the Landowner of the following described property:

____
____
____

located in _______________ County, ______________;

That the Landowner will allow the Bureau of Reclamation, its agents and assigns, hereinafter referred to as Reclamation, to place, operate, and maintain an AgriMet weather station on said property, and will allow Reclamation ingress and egress over existing access routes and other ways as may be mutually agreed upon, subject to the following terms and conditions:

1. The particular placement of the station will be determined jointly by the Landowner and Reclamation.

2. The station will be serviced and maintained by Reclamation and/or Reclamation-appointed personnel.

3. The station may be removed at any time by Reclamation, or within 30 working days if so requested by the Landowner.

4. This Permit shall remain in effect until terminated in writing by either party.

Signed: _________________________ _______________
Date

Printed Name: _________________________

Address: _________________________ _______________
Phone

____

Approved: _________________________ _______________
Bureau of Reclamation Date
AgriMet Representative

AGRIMET SITE VISIT REPORT

VISIT #

SITE NAME ____________________

SERVICE DATE ____________________ EMPLOYEE ____________________

ARRIVAL TIME ____________________ DEPARTURE ____________________

WEATHER ____

REASON FOR VISIT ____

____

____

DATA LOGGER # ____________________ TXMITTER # ____________________

CH	Description	Measured	Observed	CH	Description	Measured	Observed
#1	Batt_Volt			#16			
#2	Solar mV			#17			
#3	Precip			#18			
#4	WindDir			#19			
#5	WindSp			#20			
#6	RH			#21			
#7	AirTemp			#22			
#8	Ave_WS15m			#23			
#9	Ave_WD15m			#24			
#10	Max_WS15m			#25			
#11	Windrun			#26			
#12	Tot_Solar			#27			
#13	Tot_Precp			#28			
#14	Cal_Precp			#29			
#15	HrAve_WS			#30			

COMMENTS ____

____

____

____

____

EQUIPMENT REMOVED ____________________ BEFORE RECHARGE __________

____________________ AFTER RECHARGE __________

NEXT VISIT ____________________

EQUIPMENT INSTALLED ____________________ ____________________

____________________ ____________________

____________________ ____________________

AGRIMET FIELD CALIBRATION SHEET – CR1000

STATION:__________ ______**DATE:**_______________
START TIME:________________**END TIME:**_________________
TECHNICIANS:____
WEATHER:_______________________________________

☐ SERIAL NUMBERS

Field Licor:______________
CR1000:___________________
RMY:______________________
Precip:___________________
RH:_______________________
Raven:____________________
Regulator:________________
Solar Panel:______________
____
____
____
____

☐ SOLAR CAL

☐ Level and Clean
☐ Install surrogate
☐ Calibrate, record

Scale(~0.2):__________
Min mV (5):___________
Max mV (6):___________
Cal Time(7):__________
Accum mV (15):________

☐ Rotronic

Q Set RH_Cal = True
☐ Clean/replace filter
☐ Replace head (?)
Q Set RH_Cal = False

☐ AIR TEMP

Bench	Field

☐ Humidity

Bench	Field

☐ PRECIP CAL

1	____________	15	____________
2	____________	16	____________
3	____________	17	____________
4	____________	18	____________
5	____________	19	____________
6	____________	20	____________
7	____________	21	____________
8	____________	22	____________
9	____________	23	____________
10	____________	24	____________
11	____________	25	____________
12	____________	26	____________
13	____________	27	____________
14	____________	28	____________

☐ TIPPING BUCKET

Q Set Prec_Cal = True
TB3:798 ml=100
(Standard is +/- 3)

Before	After	# Tips

Q Set Prec_Cal = False

☐ SOIL TEMP(<20”)

Depth	Type	Bench	Field
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____

☐ RM YOUNG CHECK

☐ Clean and check level
☐ Check height (~118”)
Measured Height ______”
☐ Use shim spacer to check shaft play, torque disk to check bearings

☐ Check Wind Speed
Q Set Wind_Cal = True

RPM		Standard
500	☐	5.48
1000	☐	10.96
2000	☐	21.92
3000	☐	32.88
4000	☐	43.84
5000	☐	54.80
6000	☐	65.76

Q Set Wind_Cal = False

☐ Check Direction

☐ Point to True S 180°

Before_______ **After**_______

☐ Check 360° rotation

Degrees off_____

Swap?____

☐ Final Check

☐ Check extra screws/fuses
☐ Clean solar panel
☐ Check Work Needed
☐ Desiccant
☐ C-4 on all holes in box
☐ Check modem connection

COMMENTS

____
____
____
____
____

Executive Summary

Background and Methods

The objectives of this project focused on evaluation of the operational applications of various remote sensing methods to estimation of crop evapotranspiration (ET) over agricultural fields of the Upper Colorado River Basin (UCRB). The methods analyzed included the reconstructed METRIC method and the Simplified Surface Energy Balance operational method (SSEBop) in Colorado, New Mexico, Utah, and Wyoming. Additional space-based SSEBop estimates of ET were made in Colorado. These alternative approaches investigated the influence of: 1) the number of scenes analyzed, 2) cold pixel selection, and 3) automatic hot and cold pixel selection. Satellite methods were compared to estimates of reference evaporation in each state, respectively. A detailed comparison between the satellite methods and a direct measurement of actual evapotranspiration, measured with an Eddy Covariance (EC) tower, were performed in Colorado. The comparison between the EC tower and the satellite estimation methods was made for the subset of satellite image 'pixels' that corresponded directly to the EC tower's measurement footprint. Inter-comparisons were performed only when data from all sources were available.

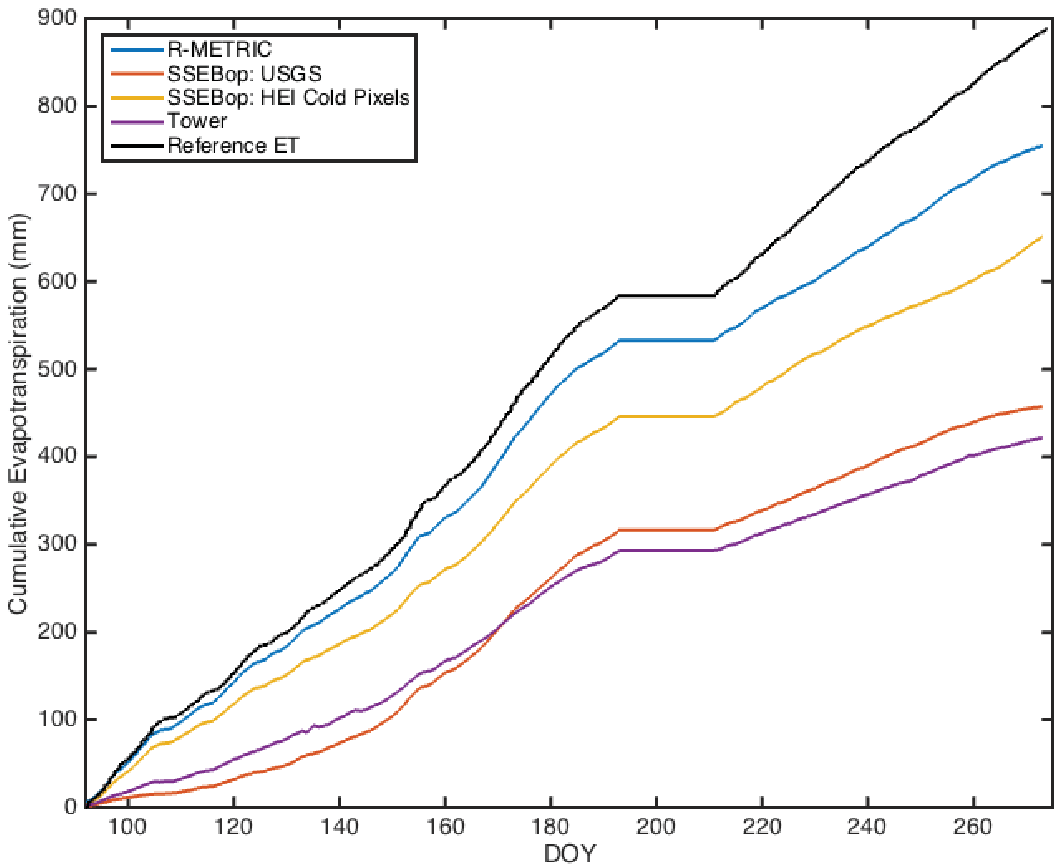


Figure 1. Comparison of EC tower cumulative ET ground-truth data for the growing season compared to various remote sensing estimating methods. Penman-Monteith Reference ET is also plotted as an upper boundary, indicating that the EC tower site near Rifle, CO was under some water stress during the 2015 growing season.

Lessons Learned

1) All remote sensing methods over-estimated cumulative seasonal evapotranspiration relative to the EC tower measurements.

2) The Penman-Monteith reference ET results were higher than any of the remote sensing estimating methods and the EC tower data indicating that the site experiences some water stress, and that all of the methods constrained the ET estimate to some degree while showing similar patterns through the season of high, moderate, and low ET days.

3) SSEBop using the U.S. Geological Survey (USGS) automated cold pixel selection and hot pixel computation was the most similar to the EC tower measurements for this particular comparison.

4) R-METRIC using hot and cold pixel selection of relatively inexperienced users, but closely following the METRIC manual guidelines, had a substantial bias and reported the highest ET of all remote sensing methods followed closely by SSEBop using the same cold pixel selection contrasted to the automated USGS procedure.

5) As has been shown in previous studies, hot and cold pixel selection is a potential source of bias. This is clearly demonstrated by the fact that the ET estimation using SSEBop increased significantly when the same cold pixel selections were used as those chosen for R-METRIC compared to the automated USGS statistically-based procedure.

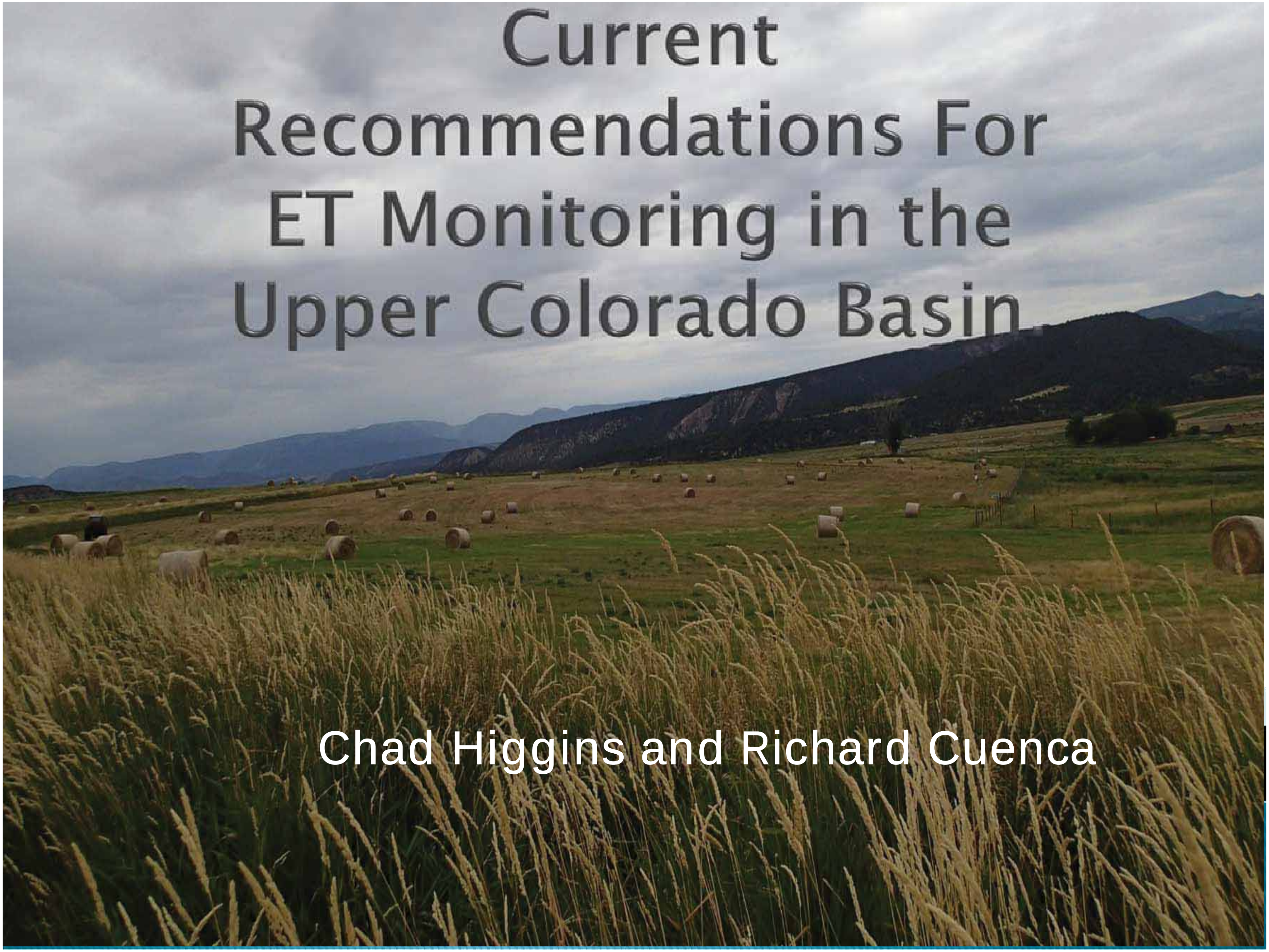
Remote sensing methods have promise and their potential for automation could lead to an economical approach to estimate agricultural consumptive water use throughout the entire basin. Space-based ET estimates are high relative to the EC tower, but the SSEBop algorithm showed the highest level of fidelity, for this comparison.

Recommendations

If the potential of space-based ET estimation is to be realized, continued confidence building in the methods of data analysis and interpretation is necessary. There is value in having a set of 'ground-truth' sites to determine the level of ET accuracy. Moving forward, a modest EC tower network is recommended that would include a minimum of one EC tower in each state of the UCRB. The purpose of this expansion is to test and build confidence in remote sensing ET estimation methods. This includes evaluating the performance of R-METRIC, SSEBop, and possibly newer methods over a wider range of climatological regimes. The influence of hot and cold pixel selection methodologies, in particular automated pixel selection methods, should be investigated in more detail. This portion of the ET estimation algorithms was a source of significant positive bias in this study. An automated boundary pixel selection procedure would also lead to labor savings. The UCRB needs to be open to new and evolving methods of ET determination using remote sensing platforms. Although Landsat 8 will remain the preferred platform for the foreseeable future, new platforms are in the planning stages and new algorithms for data analysis are evolving.

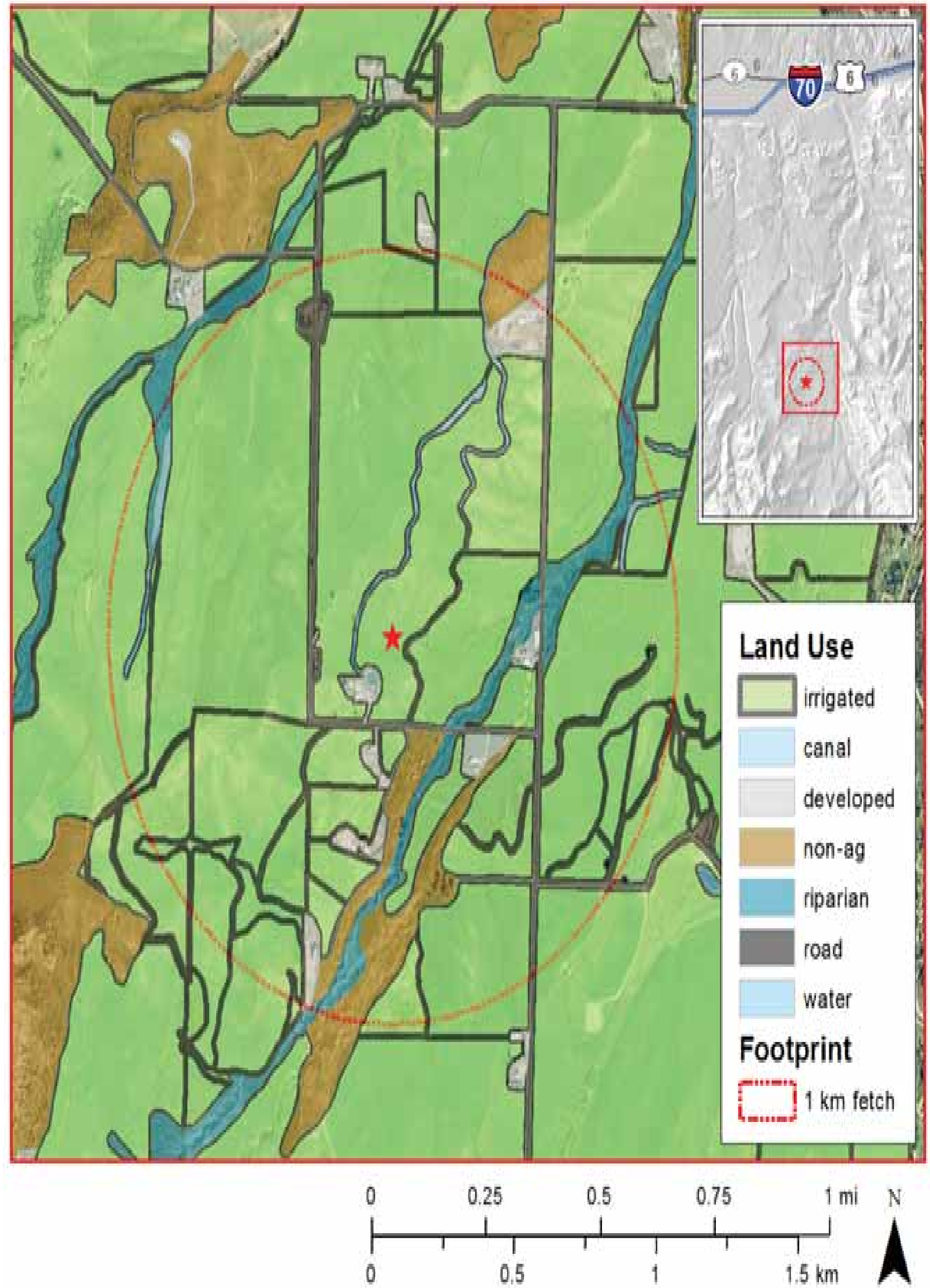
Report and Recommendations on Remote Sensing

Dr. Higgins
Hydrologic Engineering Inc.


Current Recommendations For ET Monitoring in the Upper Colorado Basin
Chad Higgins and Richard Cuenca

Eddy Covariance

- Installation just south of Silt, CO
- Operated April 1st 2015-October 2nd 2015
- Measured the actual ET from an irrigated pasture
- Can be used to 'ground-truth' other ET estimated



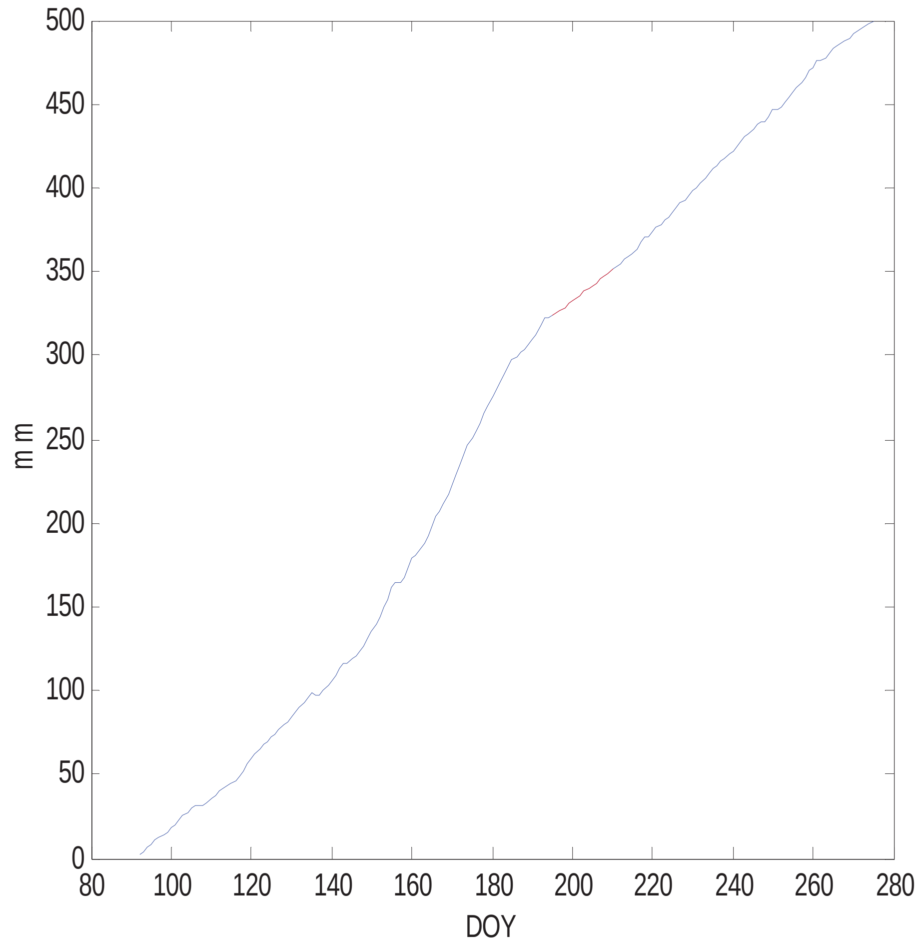
Startup and reoccurring costs: $55,000 to purchase and install, and $16,300/year to maintain

	Initial Costs	Initial Labor	Reoccurring Costs	Reoccurring labor
Sensors	$27000			
Infrastructure	$8000			
Hardware	$1000			
Telemetry	$2000		$1200/year	
Consumables			$1000/year	
Calibration			$1000/year	1 person-day/year
Installation		10 person-days		
Site Survey		1 person-day		
Site maintenance				12 person-day/year
Data analysis				0.2 FTE

Total cost estimates:

**Assuming the technician pay rate of $100/hour, benefits included, and a 20% contingency.

Measured cumulative ET for the season: 20”



Mobile or fixed?   : Fixed

- Relocating an active tower would cost ~$16,000.

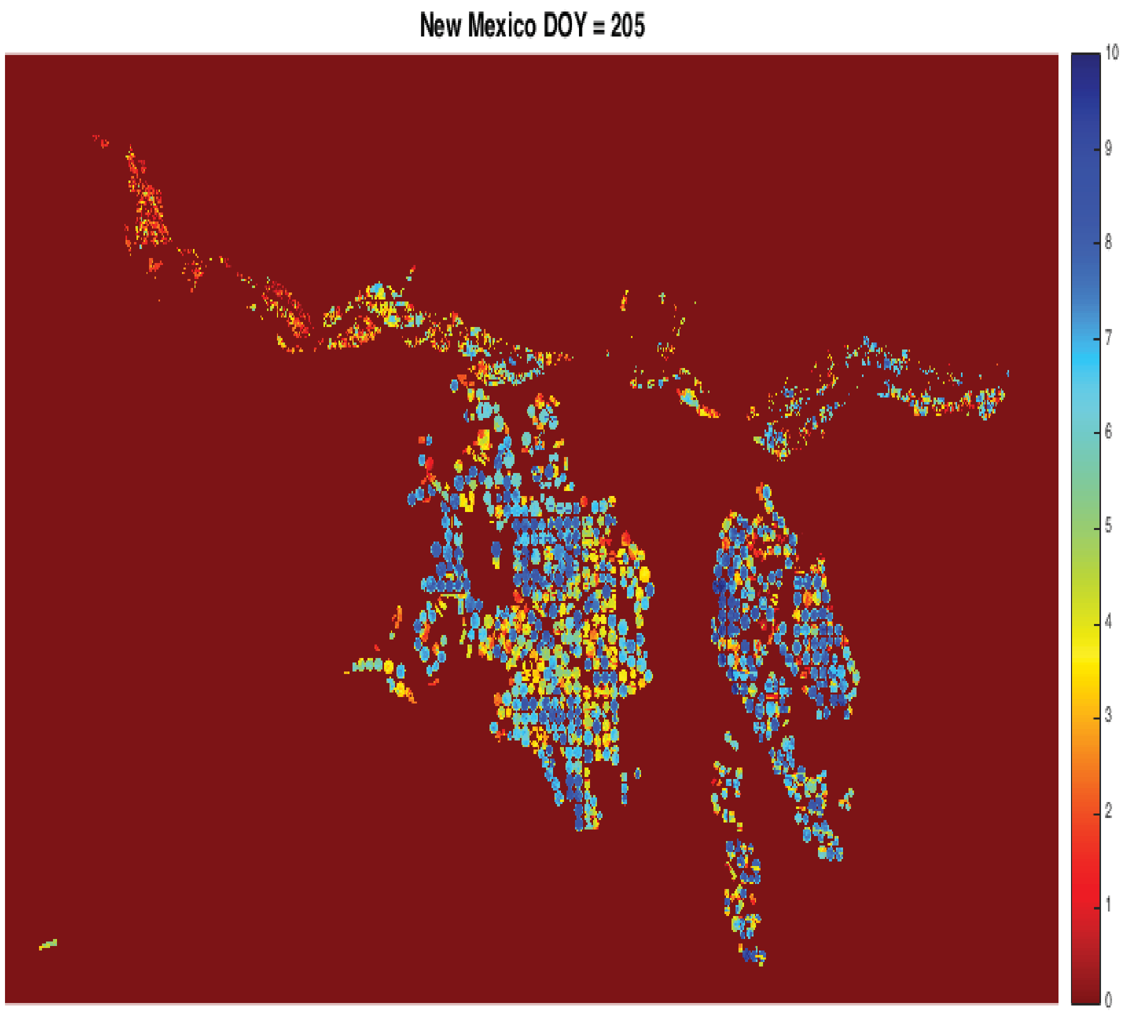
Satellite methods

<u>Advantages</u>:

- Gives an estimate of actual ET
- Directly creates a map of ETa

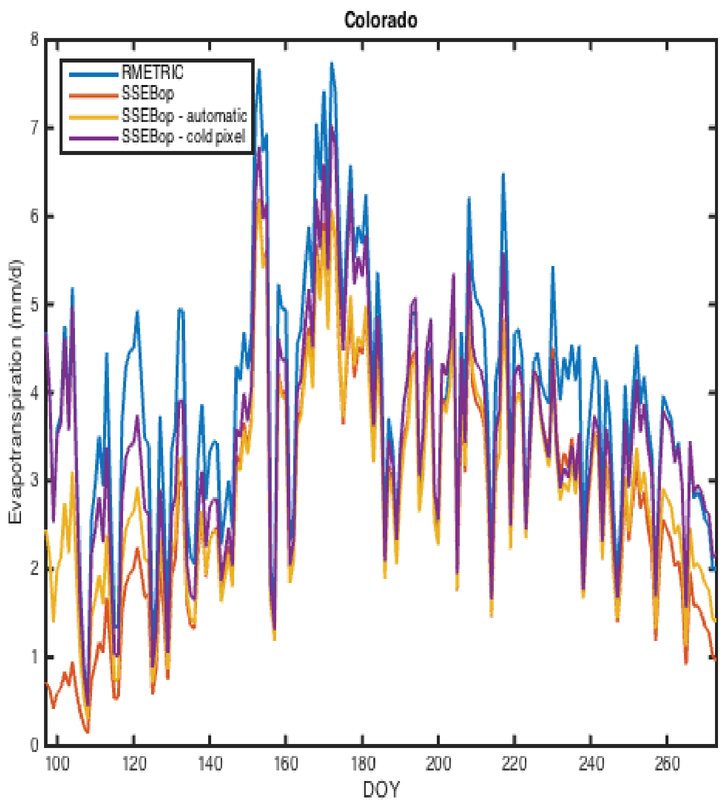
<u>Disadvantages</u>:

- Overpass every 8 days
- Clouds problematic
- Requires ground based met. Data that has gone through QA/QC.

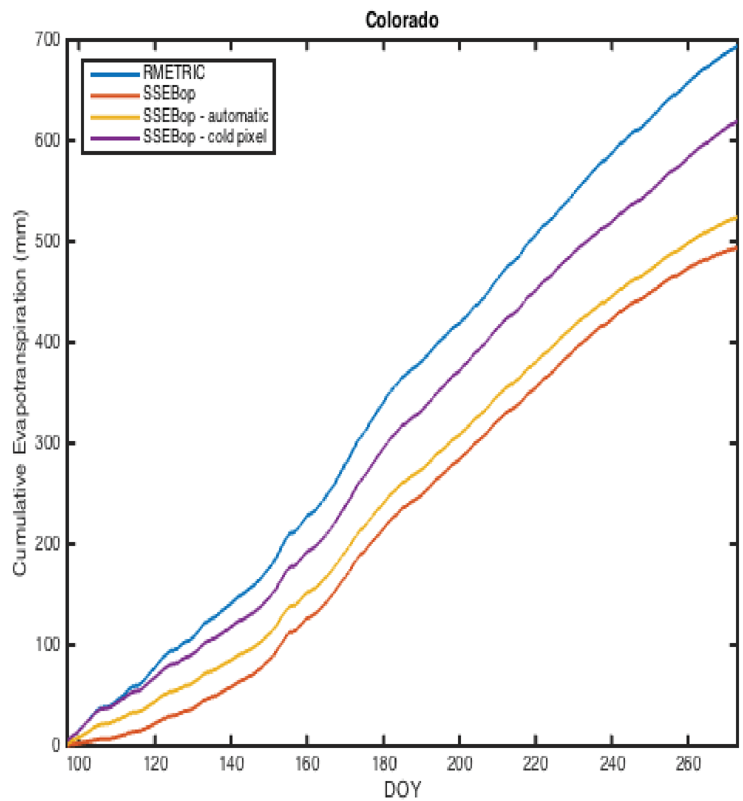


	Colorado	New Mexico	Utah	Wyoming
Path/Row	35/33	35/35	37/32	37/30
Weather Station	Olathe 2	Farmington / Block 1	Pleasant Valley	Boulder
Usable Scenes	17	19	19	15

Colorado

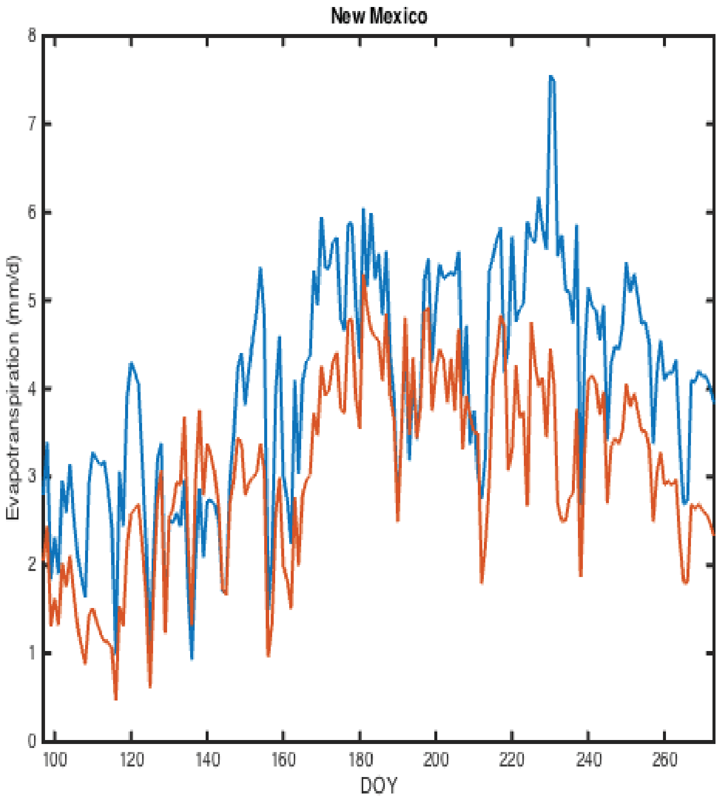


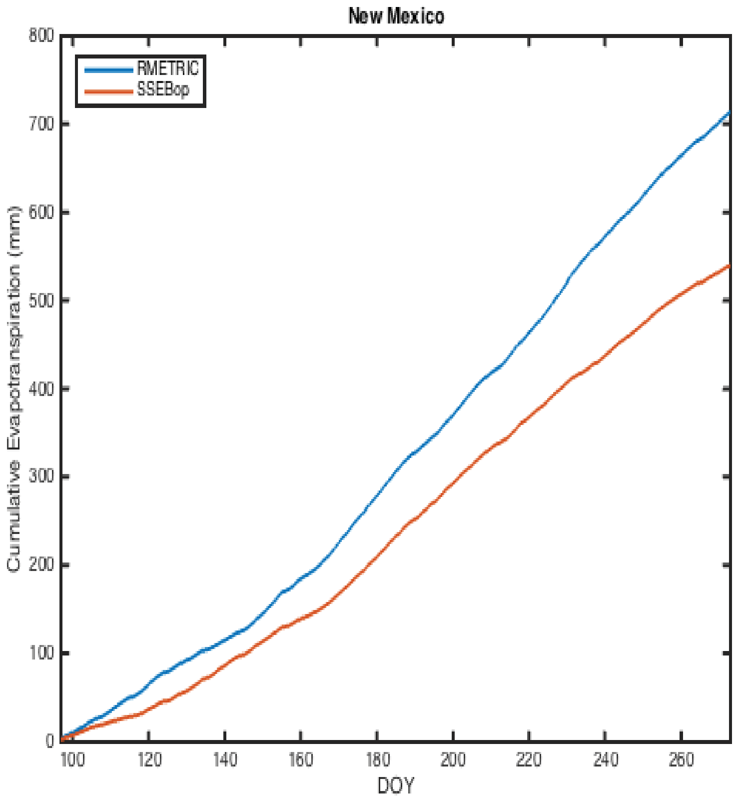
Colorado
RMETRIC
SSEBop
SSEBop - automatic
SSEBop - cold pixel
Evapotranspiration (mm/d)
DOY
0
1
2
3
4
5
6
7
8
100
120
140
160
180
200
220
240
260



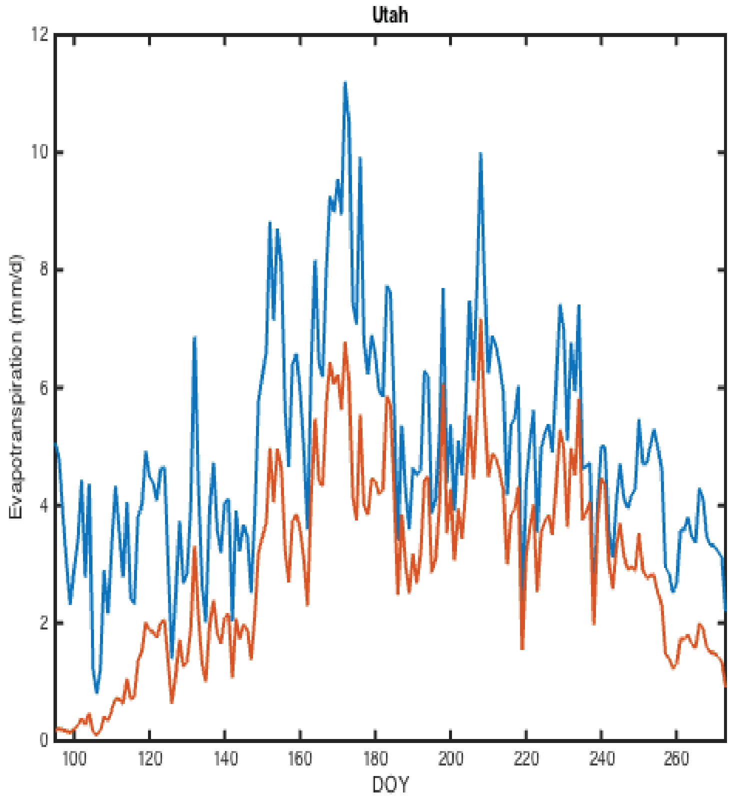
Colorado
RMETRIC
SSEBop
SSEBop - automatic
SSEBop - cold pixel
Cumulative Evapotranspiration (mm)
DOY
0
100
200
300
400
500
600
700
100
120
140
160
180
200
220
240
260

New Mexico

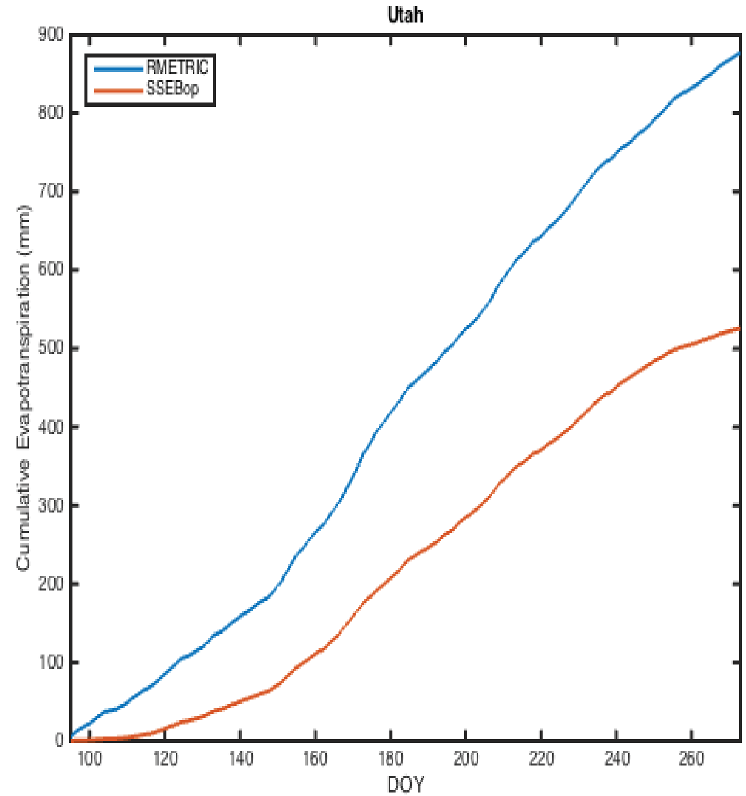

New Mexico
Evapotranspiration (mm/d)
DOY
0
1
2
3
4
5
6
7
8
100
120
140
160
180
200
220
240
260


New Mexico
RMETRIC
SSEBop
Cumulative Evapotranspiration (mm)
DOY
0
100
200
300
400
500
600
700
800
100
120
140
160
180
200
220
240
260

Utah

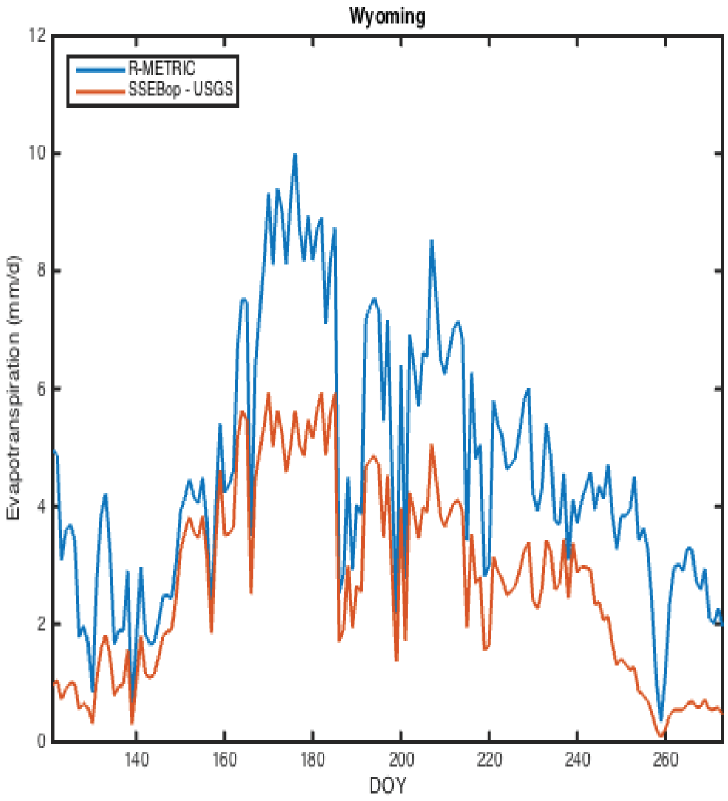


Utah
Evapotranspiration (mm/d)
DOY

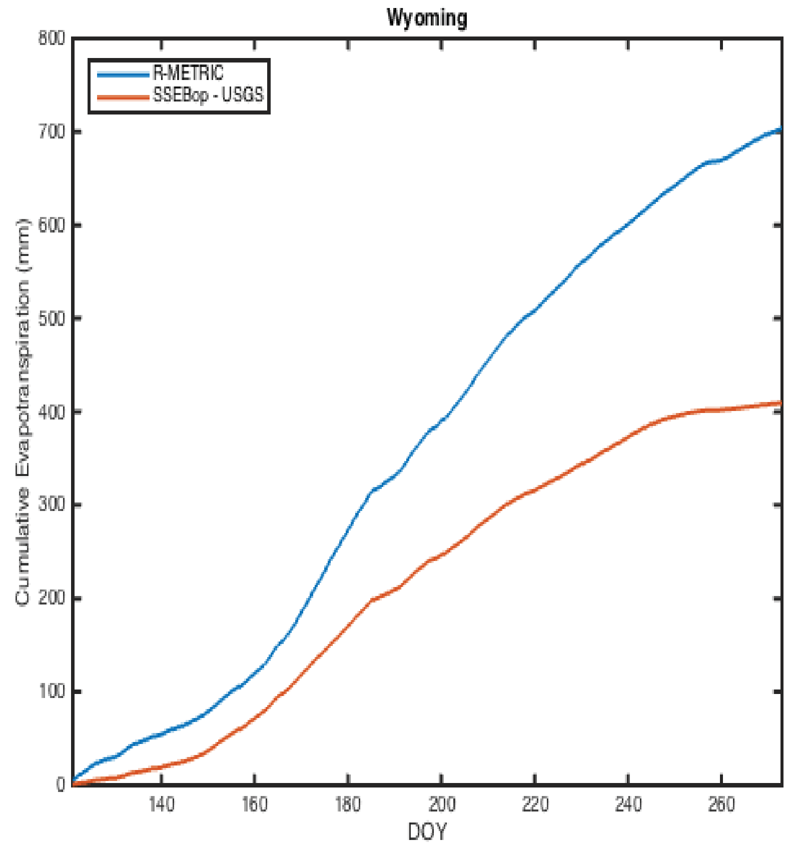


Utah
RMETRIC
SSEBop
Cumulative Evapotranspiration (mm)
DOY

Wyoming

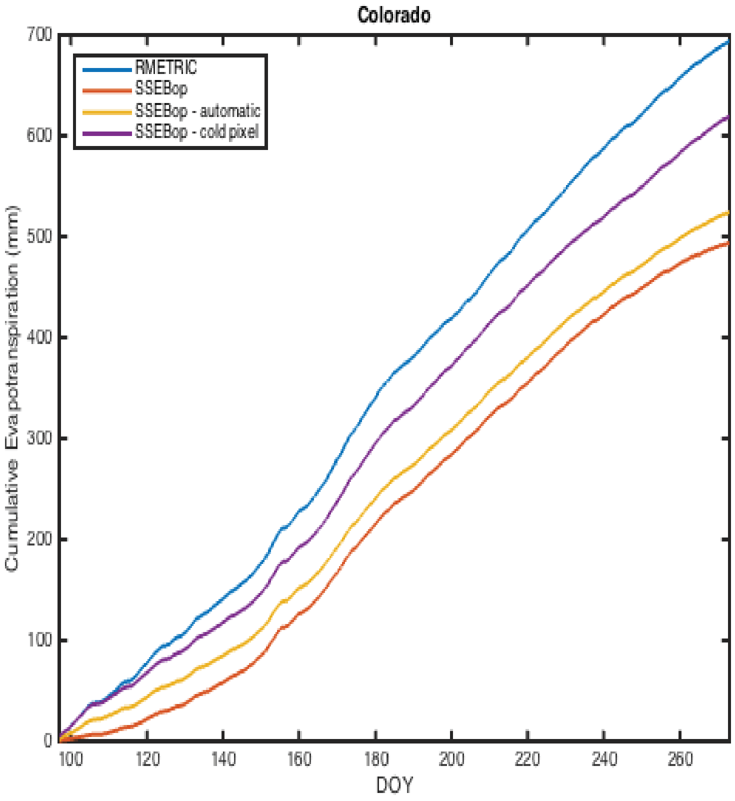


Wyoming
R-METRIC
SSEBop - USGS
Evapotranspiration (mm/d)
DOY
0
2
4
6
8
10
12
140
160
180
200
220
240
260

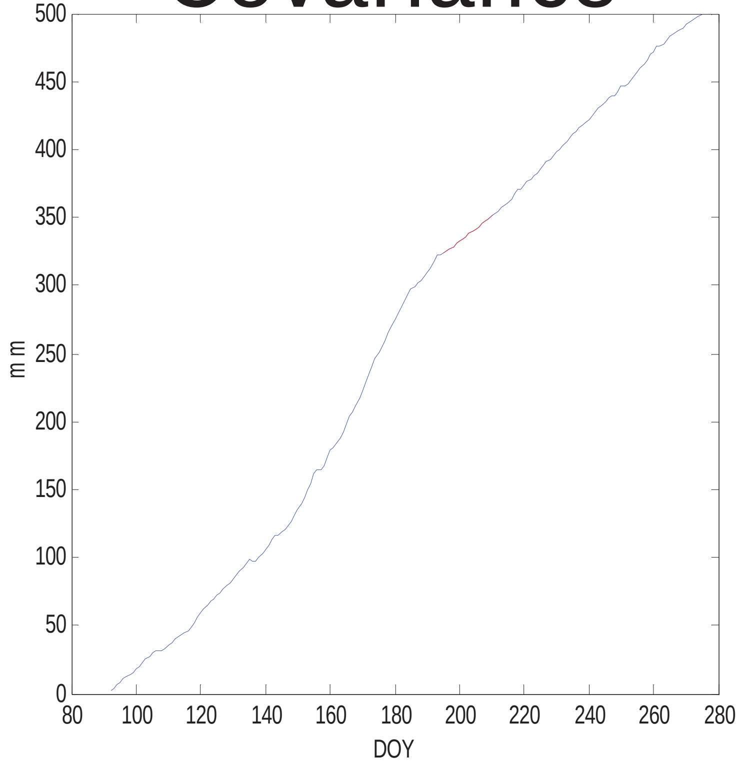


Wyoming
R-METRIC
SSEBop - USGS
Cumulative Evapotranspiration (mm)
DOY
0
100
200
300
400
500
600
700
800
140
160
180
200
220
240
260

Satellite*



**Eddy Covariance



- *Error ~20-30% for daily estimates (Senay correspondence).
- **Error ~10%

Satellite cost analysis:

Activity	Time	Done for	Total Yearly Hours
Met Data	30 minutes	Every Scene	180
Scene Preview	10 minutes	Every Scene	60
Pixel selection	30 minutes	Every Scene	180
Calculation	15 minutes	Every Scene	90
Gapfilling	5 hours	Each State Yearly	20
Interpolation	5 hours	Each State Yearly	20

0.35 FTE job to analyze entire basin (1 method), 1 week of training required for competent individual. Automation saves 180 hours/year best case.

Equipment costs: modern desktop computer with maximum RAM and hard disk space of multiple TB: $3000

Recommendations

- Rollout of satellite methods: SSEBop and RMETRIC for the entire basin
- Continue confidence building:
  - Comparisons with eddy covariance towers (1 per state). Preferred locations have been specified.
  - Comparisons with legacy methodologies should be performed.

Appendix B

MOU Concerning the UCRB and the Installation and Maintenance of Consumptive Use Instrumentation

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MEMORANDUM OF UNDERSTANDING
CONCERNING THE UPPER COLORADO RIVER BASIN AND THE INSTALLATION AND MAINTENANCE OF CONSUMPTIVE USE INSTRUMENTATION

This Memorandum of Understanding (MOU) is entered into effective this 2nd day of May, 2016, by and among the States of Colorado, New Mexico, Utah, and Wyoming; the Upper Colorado River Commission (UCRC); and the U.S. Department of Interior, Bureau of Reclamation (Reclamation).

RECITALS

The Recitals set forth below are material facts that are relevant to and form the basis for the agreement set forth herein.

I. Parties

A. State of Colorado

1. Pursuant to the executive authority of the Governor of the State of Colorado as delegated by letter dated February 6, 2015, the Director of the Colorado Water Conservation Board is authorized to negotiate and enter into this MOU.

2. Furthermore, Section 37-60-106, subsections (e), (h), (i), and (k) of the Colorado Revised Statutes empower and charge the Colorado Water Conservation Board "[t]o cooperate with the United States and the agencies thereof, and with other states for the purpose of bringing about the greater utilization of the water of the State of Colorado…; …[t]o investigate and assist in formulating a response to the plans, purposes, procedures, requirements, laws, proposed laws, or other activities of the federal government and other states which affect or might affect the use or development of the water resources of this state; [t]o confer with and appear before the officers, representatives, boards, bureaus, committees, commission, or other agencies of other states, or of the federal government, for the purpose of protecting and asserting the authority, interests, and rights of the state of Colorado and its citizens with respect to the waters of the interstate streams in this state;…[and] in general, to take such action and have such powers as are incidental to the foregoing specific provisions and to the general purposes of this article."

B. State of New Mexico

Pursuant to § 72-14-3 New Mexico Statues Annotated 1978, the New Mexico Interstate Stream Commission is authorized to investigate water supply, to develop, to conserve, to protect, and to do any and all other things necessary to protect, conserve, and develop the waters and stream systems of the State of New Mexico, interstate or otherwise. The Interstate Stream Commission is also authorized to institute or cause to be instituted in the name of the State of New Mexico any and all negotiations and/or legal proceedings as in its judgment are necessary to fulfill its statutory mandate.

C. State of Utah

The Division of Water Resources (DWR) is the water resource authority for the State of Utah. Utah Code Annotated. § 73-10-18 and § 73-10-19. § 63-34-6(1). The Utah Board of Water Resources (Board) established DWR policy. § 73-10-1.5. The Board develops, conserves, protects, and controls Utah waters, § 73-10-1.5, and, in cooperation with the Department and the Governor of Utah, supervises administration of interstate compacts, § 73-10-4, such as the Colorado River Compact, §§ 73-12a-1 through 3, and the Upper Colorado River Basin Compact, § 73-13-10. The Board, with Department and Gubernatorial approval, appoints a Utah Interstate Stream Commissioner, § 73-10-3, currently the DWR Director, to represent Utah in interstate conferences to administer interstate compacts. §§ 73-10-3 and 73-10-4. These delegations of authority authorize the Utah Interstate Stream Commissioner/DWR Director to sign this document. He acts pursuant to a Board resolution, acknowledged by the Department, dated December 9, 2010.

D. State of Wyoming

Water in Wyoming belongs to the state. Wyo. Const. Art. 8 § 1. The Wyoming State Engineer is a constitutionally created office and is Wyoming's chief water official with general supervisory authority over the waters of the State. Wyo. Const. Art. 8 § 5. The Wyoming legislature conferred upon Wyoming officers the authority to cooperate with and assist like authorities and entities of other states in the performance of any lawful power, duty or authority. Wyo. Stat. Ann. § 16-1-101. Wyoming and its State Engineer represent the rights and interests of all Wyoming appropriators with respect to other states. *Wyoming v. Colorado*, 286 U.S. 494 (1922). *See Hinderlider v. La Plata River & Cherry Creek Ditch Co.*, 304 U.S. 92 (1938). Furthermore, the Wyoming State Engineer, as Wyoming's appointed Commissioner under the Upper Colorado River Basin Compact, has full authority to make any and all investigations necessary related to the Colorado River system. Wyo. Stat. Ann. § 41-11-203.

E. U.S. Department of Interior, Bureau of Reclamation (Reclamation)

Reclamation is acting pursuant to the Reclamation Act of June 17, 1902 (32 Stat. 388), and acts amendatory thereof or supplementary thereto, particularly Title VI of the 1968 Colorado River Basin Project Act (P.L. 90-537), which authorizes and directs Reclamation to make reports of the annual consumptive uses and losses of water from the Colorado River System in consultation with the Upper Colorado River Commission.

F. Upper Colorado River Commission (UCRC)

Article VI of the Upper Colorado River Compact directs that the UCRC shall determine the quantity of consumptive use of water in the Upper Basin; Article VIII directs that the UCRC shall have the power to, among other things, make findings as to the quantity of water used each year in the Upper Colorado River Basin and in each Upper Basin state.

II. Background

The four states of the Upper Division (Colorado, New Mexico, Utah, and Wyoming), through the UCRC, and in cooperation with Reclamation, initiated a study to assess and improve consumptive use estimates from irrigated agricultural lands in the Upper Colorado River Basin. That study, Assessing Agricultural Consumptive Use in the Upper Colorado River Basin (Phase I, December 2013) and Phase II (anticipated 2016), resulted in a recommendation that several weather stations (existing and new) be formally identified for the purpose of providing information for consumptive use estimates from irrigated lands. In addition, the study suggested the installation of several eddy covariance towers be considered to support further independent verification of ET estimates in the upper basin. The data collected from this "Upper Basin Climate Network"[1] (UB Network) will be utilized in ongoing studies associated with assessing consumptive use calculations. These studies are important to the individual states, the UCRC, and Reclamation. The identified UB Network consists of existing weather stations, existing weather stations with necessary upgrades to meet the standards set by ASCE-EWRI 2005, new weather stations which will be installed in accordance with the ASCE-EWRI 2005 protocols, and four new eddy covariance tower stations.

Given the time and resources spent on the Phase I and II studies and the upgraded and newly installed stations, as well as the importance of the UB Network for consumptive use estimates in the Upper Colorado River Basin, the parties want to ensure the stations will continue to be operated and maintained to an agreed level of standards, and that all collected data will be made available to any and all users in a consistent format.

The Parties desire to enter into this MOU to outline the necessary funding levels and funding sources, as well as staffing resources that are estimated to be needed to set-up and operate the described UB Network over the next 10 years (i.e., through 31 December, 2025).

---

[1] The term "Upper Basin Climate Network" (UB Network) is used here to describe the group of weather stations and eddy covariance tower stations that will provide data for consumptive use estimates from irrigated lands within the Upper Colorado River Basin. Many of these stations (in subsets) already belong to an official network owned and operated by a state, federal, or other entity as outlined below.

III. Upper Basin Network Description

There are a total of 54 stations under consideration for the UB Network. This includes 26 weather stations in Colorado, 2 in New Mexico, 12 in Utah, and 10 in Wyoming. Of these, 36 weather stations currently exist or are planned to be installed in the near future. Fourteen (14) additional weather stations are proposed as part of this MOU.

Also planned for the network is the installation of four new eddy covariance tower stations (one in each of the four states). General locations of each tower are identified in the Phase II Consumptive Use report. Final locations will be determined in discussions between each state and the eddy covariance consultant to be hired.

Attachment A contains the details of individual stations and estimated costs for the proposed installation of new stations being considered as part of this MOU. Attachment A contains the following information:

Table 1. Table 1 lists existing stations or those planned for installation within other operated networks. These stations are funded by their respective network owners. It is anticipated that operation of these stations will continue under existing funding mechanisms to the extent possible. There are 36 stations listed in Table 1.

Table 2. Table 2 lists 14 new weather stations proposed as part of this MOU that have been identified as important to the UB Network to provide adequate coverage of irrigated lands in the Upper Basin. The identified state or network owner will become responsible for the operation and maintenance of these stations after the first year of operation (i.e., after 31 December, 2016), subject to the provisions of Section IV.

Table 3. Table 3 is a summary of the estimated funds necessary to install and operate the 14 new weather and 4 new eddy covariance stations for the term of this MOU. Also shown in Table 3 is the breakdown of funding sources known to date, as well as unsecured funding needs.

IV. Purposes

The Parties to this MOU intend that their respective actions contemplated in this MOU will result in improved and standardized collection of climatic data from automated weather stations (stations) as well as actual ET measurements from selected locations. Together, these data will serve to provide better consumptive use information for each individual state as well as the upper basin as a whole. The Parties agree as follows:

1. The States, the UCRC, and Reclamation will work together to provide for the installation and continued operation and maintenance of all 54 stations identified in Attachment A.

2. The weather stations will be maintained and operated according to the American Society of Civil Engineers (ASCE) standards appropriate for operation and maintenance of this network (ASCE-EWRI 2005). The EC towers will be maintained according to the recommendations of the manufacturer and the consultant in charge.

3. The quality assurance and quality control (QA/QC) data from all stations will be freely available and accessible to all parties, provided that, an agreement providing for sharing and accessibility of the data produced by those stations owned by entities which are not party to this agreement is successfully negotiated between the State(s) in which such station(s) reside and the owner(s).

4. Installation and the first year of operation costs for the 14 new weather stations as well as installation costs for the EC towers will be paid directly by the Bureau of Reclamation. Until fully expended, subsequent O&M costs for all stations will be covered under the approved Consumptive Use Project funds from the Basin Fund MOA. Any additional funding through the Basin Fund MOA must be requested separately and approved through the MOA process. Thereafter, each State or owner of the respective network is responsible for the operation and maintenance of its respective stations, provided that; (a) sufficient funding is appropriated by each State's respective legislature, and (b) an agreement providing for the operation and maintenance for those stations owned by entities which are not party to this agreement is successfully negotiated between the State(s) in which such station(s) reside and the owner(s). Should funding issues arise, the States will notify the UCRC as soon as possible so that alternative funding sources may be identified.

5. This MOU is subject to appropriations being made by Congress from year to year of funds sufficient to conduct the work provided herein. No liability shall accrue to the United States by reason of such funds not being appropriated.

6. This agreement does not ensure long-term funding from any State or Reclamation for operation and maintenance of the weather stations. Rather, the States and Reclamation will work toward securing long-term funding for operation of the network of weather stations in each of their Upper Division States.

It is recognized that differing mechanisms exist within each state for the funding and operation of existing stations, which are:

1. Colorado – The stations are operated through the Colorado Agricultural Meteorological Network (CoAgMet), a program of the State Climatologist located within the Colorado State University System.

2. New Mexico – The stations are operated through the New Mexico Climate Center at New Mexico State University.

3. Utah – The stations are operated by Reclamation's agricultural weather network (AgriMet) system, in association with Utah State University.

4. Wyoming – The stations are operated by the Wyoming State Engineer's Office as part of the Wyoming Agricultural Climate Network (WACNet).

V. Duration of Agreement

This MOU will remain in effect through 31 December, 2025 unless terminated sooner by all Parties.

VI. Modification

This MOU may be modified at any time upon mutual consent of all parties. Furthermore, the UB Network identified through this MOU may be modified as recommended by the residing State, and upon notification of the UCRC.

VII. Withdrawal

Any party may withdraw from this MOU upon 30 days' written notice to all Parties. If any party does withdraw from this MOU, steps shall be taken to ensure that the withdrawal does not affect any prior obligation, project or activity already in progress by the remaining parties.

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JAMES EKLUND
State of Colorado

DEBORAH K. DIXON
State of New Mexico

ERIC L. MILLIS
State of Utah

PATRICK T. TYRRELL
State of Wyoming

DON A. OSTLER, Executive Director
Upper Colorado River Commission

BRENT RHEES, Regional Director
Upper Colorado Region
Bureau of Reclamation

ATTACHMENT A

Table 1 lists stations that currently exist or are planned for installation within other operated networks. These stations are funded by their respective network owners. Operation of these stations will continue under existing funding mechanisms to the extent possible. There are 36 stations listed in Table 1.

Table 1

Station Name	Climate Network	State
Bridger Valley	WACNet	WY
Boulder	WACNet	WY
Daniel	WACNet	WY
Budd Ranch	WACNet	WY
Upper Green	WACNet	WY
Henry's Fork	WACNet	WY
Farson	WACNet	WY
Little Snake Valley	WACNet	WY
La Barge	WACNet	WY
Granger	WACNet	WY
Pleasant Valley	AgriMet	UT
Duchesne	AgriMet	UT
Pelican Lake	AgriMet	UT
Elmo	AgriMet	UT
Huntington	AgriMet	UT
Ferron	AgriMet	UT
Castle Dale	AgriMet	UT
Tropic (Paria River)	AgriMet	UT
Castle Valley near Moab	AgriMet	UT
Delta	CoAgMet	CO
Montrose	CoAgMet	CO
Olathe	CoAgMet	CO
Olathe 2	CoAgMet	CO
Eckert	CoAgMet	CO
Gunnison	CoAgMet	CO
Yellow Jacket	CoAgMet	CO
Silt Mesa	CoAgMet	CO
CSU Fruita Expt Station	CoAgMet	CO
Roaring Fork Valley	CoAgMet	CO
Hayden	CoAgMet	CO
Upper Uncompahgre	CoAgMet	CO
Orchard Mesa	CoAgMet	CO

Station Name	Climate Network	State
Mancos	CoAgMet	CO
Cortez	CoAgMet	CO
Towaoc	CoAgMet	CO
Farmington	NMCC	NM

AgriMet = Bureau of Reclamation agricultural weather network
CoAgMet = Colorado Agricultural Meteorological Network
NMCC = New Mexico Climate Center
WACNet = Wyoming Agricultural Climate Network

Table 2 lists 14 new stations that have been identified as important to the Upper Colorado River Basin Network (UB Network) to have adequate coverage of irrigated lands in the Upper Colorado River Basin.

TABLE 2

Station Name	Climate Network	State	Responsible Party[1]
Los Pinos River	CoAgMet	CO	CO - WCB
Kremmling	CoAgMet	CO	CO - WCB
Steamboat Springs	CoAgMet	CO	CO - WCB
Collbran	CoAgMet	CO	CO - WCB
San Miguel	CoAgMet	CO	CO - WCB
Marvine Ranch	CoAgMet	CO	CO - WCB
Animas/Florida River	CoAgMet	CO	CO - WCB
Fraser/Upper Colorado	CoAgMet	CO	CO - WCB
La Plata River	CoAgMet	CO	CO - WCB
Pagosa Springs	CoAgMet	CO	CO - WCB
Neola Area	AgriMet	UT	UT - DWR
Vernal	AgriMet	UT	UT – DWR
Loa/Bicknell Area	AgriMet	UT	UT - DWR
Aztec	NMCC	NM	NM - ISC

Notes:
[1] Subject to the provisions of Section IV.
CO – WCB: Colorado Water Conservation Board
NM – ISC: New Mexico Interstate Stream Commission
UT – DWR: Utah Division of Water Resources

AgriMet = Bureau of Reclamation agricultural weather network
CoAgMet = Colorado Agricultural Meteorological Network
NMCC = New Mexico Climate Center

or the Upper Basin Climate Network.[1]

e	Install Cost	1	2	3	4	5	6	7	8
							O&M Costs by Year		
	$9,000	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,25
	$9,000	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,25
	$9,000	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,25
	$9,000	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,25
	$9,000	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,25
	$9,000	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,25
	$9,000	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,25
	$9,000	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,25
	$9,000	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,25
	$9,000	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,25
	$8,000	***	***	***	***	***	***	***	***
	$9,000	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,25
	$9,000	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,25
	$9,000	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,25
1	$9,000	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,25
1	$0	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,250	$2,25
1	$8,000	***	***	***	***	***	***	***	***
	$18,000	***	***	***	***	***	***	***	***
	$160,000	$33,750	$33,750	$33,750	$33,750	$33,750	$33,750	$33,750	$33,75
	$55,000	$16,300	$16,300	$16,300	$16,300	$16,300	$16,300	$16,300	$16,30
	$55,000	$16,300	$16,300	$16,300	$16,300	$16,300	$16,300	$16,300	$16,30
1	$55,000	$16,300	$16,300	$16,300	$16,300	$16,300	$16,300	$16,300	$16,30
	$55,000	$16,300	$16,300	$16,300	$16,300	$16,300	$16,300	$16,300	$16,30
	$220,000	$65,200	$65,200	$65,200	$65,200	$65,200	$65,200	$65,200	$65,20
	$380,000	$98,950	$98,950	$98,950	$98,950	$98,950	$98,950	$98,950	$98,95
				Unsecured Funding by State					
3,750				CO	$149,000				
8,500				NM	$95,000				
7,250				UT	$101,750				
				WY	$81,500				
9,500					$427,250				

[1] - Table 3 – Explanation of Funding

Funding Source:

Bureau of Reclamation $413,750

- These are funds contributed by the Bureau of Reclamation from drought funds received in federal FY2016. The total is the estimated installation cost for the fourteen new climate stations ($160,000) and four new eddy covariance towers ($220,000), as well as the first year of O&M for the fourteen climate stations ($33,750). These costs are highlighted in yellow in Table 3.

Approved MOA Funds $528,500

- These are MOA funds requested by the states and approved by the Bureau of Reclamation as part of the ongoing Upper Basin Consumptive Use Project. These funds will be used to cover the cost of O&M for the fourteen climate stations for years two through seven ($202,500), and the cost of O&M for the four eddy covariance towers for years one through five ($326,000). These costs are highlighted in blue in Table 3.

Unsecured Funding Needs $427,250

- This is the cost of yet unsecured funding to cover the cost of O&M for the fourteen climate stations for years eight through ten ($101,250), and the cost of O&M for the four eddy covariance towers for years six through ten ($326,000). These costs are not highlighted in Table 3

Unsecured Funding by State:

Based upon the location of individual climate stations and eddy covariance towers, the breakout of unsecured funding by each state is listed below. As described in the MOU, each respective state agrees to seek funding to meet these needs, but no state has fully committed to cover these costs.

Colorado	$149,000
New Mexico	$ 95,000
Utah	$101,750
Wyoming	$ 81,500
TOTAL	**$427,250**

Cited References:

American Society of Civil Engineers – Environmental and Water Resources Institute (ASCE-EWRI). 2005. The ASCE Standardized Reference Evapotranspiration Equation. By Richard G. Allen (editor), Ivan A. Walter (editor), Ronald L. Elliott (editor), Terry A. Howell (editor), Daniel Itenfisu (editor), Marvin E. Jensen (editor), and Richard L. Snyder (editor), EWRI, Reston, VA. Prepared by the Task Committee on Standardization of Reference Evapotranspiration of the Environmental and Water Resources Institute of ASCE.

URS, CH2MHill, Hydrologic Engineering, Inc., and Wilson Water Group. 2013. *Assessing Agricultural Consumptive Use in the Upper Colorado River Basin. Phase I Study.* Report prepared and submitted to the Upper Colorado River Commission and the Bureau of Reclamation. 160 pages. November.

URS, CH2MHill, Hydrologic Engineering, Inc., and Wilson Water Group. Anticipated 2016. *Assessing Agricultural Consumptive Use in the Upper Colorado River Basin. Phase II Study*. Report prepared and submitted to the Upper Colorado River Commission and the Bureau of Reclamation.

Appendix C

Mathematical Foundations of the Eddy Covariance Technique

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Eddy Covariance (EC) Theory and Development of the Equations

Start with the advection dispersion equation which describes the motion of water vapor within the atmospheric boundary layer:

$$\frac{\partial q}{\partial t}+\frac{\partial(uq)}{\partial x}+\frac{\partial(vq)}{\partial y}+\frac{\partial(wq)}{\partial z}=D\left(\frac{\partial^2 q}{\partial x^2}+\frac{\partial^2 q}{\partial y^2}+\frac{\partial^2 q}{\partial z^2}\right). \tag{1.2}$$

Where q is the specific humidity in (g/m^3), the 3-D wind velocity vector is $u\hat{i}+v\hat{j}+w\hat{k}$, and the mass diffusivity of air is D. The atmospheric flow is assumed to be turbulent. Under this condition, the transport due to advection is much more efficient than the transport of water vapor due to diffusion. Equation A.1 reduces to:

$$\frac{\partial q}{\partial t}+\frac{\partial(uq)}{\partial x}+\frac{\partial(vq)}{\partial y}+\frac{\partial(wq)}{\partial z}=0. \tag{1.3}$$

Horizontal homogeneity is assumed. That is, the measurement location is assumed to be above a land surface that is relatively flat and uniform. This assumption reduces derivatives in the x and y directions to zero.

$$\frac{\partial q}{\partial t}+\frac{\partial(wq)}{\partial z}=0 \tag{1.4}$$

Reynolds decomposition (REF) is employed. Here, the vertical velocity w, and the specific humidity q are decomposed into a mean component and a fluctuating component:

$$\frac{\partial(\overline{q}+q')}{\partial t}+\frac{\partial(\overline{w}+w')(\overline{q}+q')}{\partial z}=0. \tag{1.5}$$

Where the overbar represents the average of the quantity and q' and w' are the turbulent fluctuations in the specific humidity and the vertical component of the wind velocity vector, respectively. The mean of the vertical velocity component, $\overline{w}$ is assumed to be zero, which leads to:

$$\frac{\partial(\overline{q}+q')}{\partial t}+\frac{\partial(w'\overline{q}+w'q')}{\partial z}=0. \tag{1.6}$$

Equation 1.5 is then averaged over many events. By definition, isolated fluctuating quantities have a zero average. This is a mathematical consequence, not an assumption:

$$\frac{\partial(\overline{q})}{\partial t}+\frac{\partial(\overline{w'q'})}{\partial z}=0. \tag{1.7}$$

Now the mean humidity is assumed to be quazi-stationary. That is, the average humidity is changing slowly with time. This assumption eliminates the time derivative term to produce:

$$\frac{\partial(\overline{w'q'})}{\partial z} = 0\,. \tag{1.8}$$

Interpretation of 1.7 reveals that the average advection of humidity in the vertical direction is constant near the land surface.

$$\overline{w'q'} = \text{constant} \tag{1.9}$$

Thus, the measured covariance between the vertical component of the wind velocity and the humidity within the air column above the land surface is the same as the evaporation at the land surface, providing the assumptions outlined above are satisfied.

Atmospheric stability can be calculated as:

$$Stability = -\frac{\frac{z_m g \kappa}{\theta_v}\overline{w'\theta'_v}}{\left(-\overline{u'w'}\right)^{3/2}} \tag{1.10}$$

Where g is the acceleration due to gravity, κ is the Von Karaman constant = 0.41, and θ_v is the sonic temperature.

Appendix D

Sensor and Anemometer Manufacturer Information

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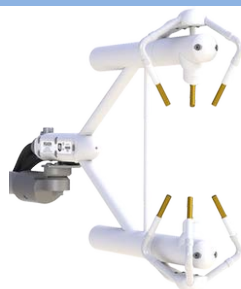
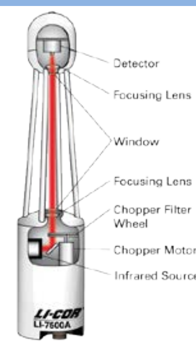
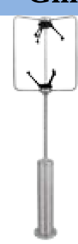
There are two dominant manufacturers of open path instruments (like the type pictured on Figure 3-1). These manufacturers are Campbell Scientific, who produces the EC150 probe and the integrated IRGASON system, and Licor, who produces the LI7500A probe. All three sensors are of sufficient quality and accuracy to perform EC.

Manufacturer	Campbell Scientific IRGASON	Campbell Scientific EC150	Licor LI7500A
Photo: Promotional Material from Manufacturers			
Output bandwidth	20 Hertz	20 Hertz	20 Hertz
Accuracy	2%	2%	2%

A range of manufacturers provide suitable anemometers. Major providers include: Campbell Scientific, Gill, Metek, and Young. Each instrument has unique attributes and configurations.

Manufacturer	Campbell Sci.	Gill	Metek	Young
Photo: Promotional Material from Manufacturers				
Measurement Range	0-134 miles/hour	0-145 miles/hour	unspecified	0-89 miles/hour
Max Repetition	60 Hertz	32 Hertz	50 Hertz	32 Hertz
Vertical Wind Resolution	0.02 inches/second	0.4 inches/second	0.4 inches/second	0.4 inches/second

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Appendix E

Cost Quotes for an Integrated IRGASON Sensor with a CR6 Data Logger and for an LI7500A with a Gill Sonic Anemometer and Licor Logging System

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CAMPBELL SCIENTIFIC
WHEN MEASUREMENTS MATTER
815 West 1800 North • Logan, Utah 84321-1784
Phone 435.227.9000 • Fax 435.227.9091
Fed. I.D. #87-0305157 • DUNS#06-798-0730

Quote Number	137200
Quote Date	11-16-15
Valid Through Date	01-15-16
Quoted By	Benjamin Conrad
Customer Number	4984
Est. Ship ARO	21 Days ARO
Page	1

Domestic Sales Quotation

QUOTE TO	SHIP TO
Jason Kelley Oregon State University Biological & Ecological Eng Dept 116 Gilmore Hall Corvallis, OR 97331-3906 United States	

Contact:	Jason Kelley	Cust RFQ:	
Phone:	541-760-7796	Terms:	Net 30 Days
Fax:		Freight Terms:	
Email:	kelleyja@oregonstate.edu	Incoterm:	FOB Logan, UT

Li	Model	Part	Description	Qty	UM	Unit Price	Ext. Price
	Manual Distribution: Send 1 Resource DVD. The items listed below are quoted as per customer request and DO NOT necessarily "make-up" a complete system. Some items requested may not be compatible with one another or require additional peripherals for hardware integration. The Dataloggers do not arrive pre-programmed. Please consult the application engineer listed above to review any and all concerns when implementing a full or partial system. A typical application will include: Datalogger, Sensors, Power Options, Communication Options, Environmental Enclosure, Mounting Hardware and PC Support Software.						
1	IRGASON-BB-IC	27350-1	Integrated CO2/H2O Open-Path Gas Analyzer & 3D Sonic Anemometer -BB Basic Barometer -IC IRGASON Carrying Case	1	EA	18,998.40	18,998.40
2	CABLEPCBL-L35-PT	21969-50	2-Conductor 16AWG Power Cable 35ft per cable -PT w/Tinned Wires	1	EA	89.85	89.85
3	CABLE4CBL-L35-PT	21972-53	4-Conductor 22AWG Cable w/Drain 35ft per cable -PT w/Tinned Wires	1	EA	79.10	79.10
						Continued	

This Quote is for Domestic purposes only. Authorized Signature X______________________

Terms and conditions with Campbell Scientific are governed by the terms found at http://www.campbellsci.com/terms.

CAMPBELL SCIENTIFIC
WHEN MEASUREMENTS MATTER

815 West 1800 North • Logan, Utah 84321-1784
Phone 435.227.9000 • Fax 435.227.9091
Fed. I.D. #87-0305157 • DUNS#06-798-0730

Quote Number	137200
Quote Date	11-16-15
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Est. Ship ARO	21 Days ARO
Page	2

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Contact:	Jason Kelley	Cust RFQ:	
Phone:	541-760-7796	Terms:	Net 30 Days
Fax:		Freight Terms:	
Email:	kelleyja@oregonstate.edu	Incoterm:	FOB Logan, UT

Li	Model	Part	Description	Qty	UM	Unit Price	Ext. Price
4		26390	IRGASON & EC150 Zero & Span Shroud Kit	1	EA	422.40	422.40
5		27278	IRGASON & EC150 Lab Stand Kit	1	EA	153.60	153.60
6		NOTE	************************* Datalogger *************************	1	EA	0.00	0.00
7	CR6-NA-ST-SW	28385-5	Measurement & Control Datalogger -NA No Additional Coms -ST -40 to +70C -SW Standard 3yr Warranty	1	EA	1,824.00	1,824.00
8	CR1000KD	16136	Keyboard/Display for CR1000, CR800, or CR6	1	EA	268.80	268.80
9	29796-US	29796-1	Power Supply 24Vdc 1.67A Output, 100-240Vac 1A Input, 5ft Cable -US US & Canada Plug	1	EA	28.80	28.80

Continued

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Phone 435.227.9000 • Fax 435.227.9091
Fed. I.D. #87-0305157 • DUNS#06-798-0730

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Jason Kelley Oregon State University Biological & Ecological Eng Dept 116 Gilmore Hall Corvallis, OR 97331-3906 United States	

Contact:	Jason Kelley	Cust RFQ:	
Phone:	541-760-7796	Terms:	Net 30 Days
Fax:		Freight Terms:	
Email:	kelleyja@oregonstate.edu	Incoterm:	FOB Logan, UT

Li	Model	Part	Description	Qty	UM	Unit Price	Ext. Price
10		27158	2GB microSD Flash SLC Memory Card	2	EA	38.40	76.80
11	ENC12/14-SC-TM	30707-94	Weather-Resistant 12 x 14 inch Enclosure -SC 1 Conduit for Cables -TM Tower Mounting	1	EA	283.20	283.20
12		NOTE	************************* No power or mounting is quoted. No software or program is quoted.	1	EA	0.00	0.00
						SUBTOTAL	$22,224.95
						TAX	$0.00
						FREIGHT	TO BE ADDED
						TOTAL	$22,224.95

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QUOTATION

LI-COR Biosciences

LI-COR, Inc.
4421 Superior St
Lincoln, NE 68504 USA
Phone: 402-467-3576
US & Canada: 800-447-3576
Fax: 402-467-2819
www.licor.com
envsales@licor.com

FEDERAL ID NO: 47-0537101
DUNS NO: 06-223-7961

Jason Kelley
Oregon State University
116 Gilmore Hall
Corvallis, OR 97331-3906
UNITED STATES

QUOTE NO: L56573-1
QUOTE DATE: 16/November/2015

Your Reference No.	Quote Expires	Payment Terms
Request for Quotation	16/March/2016	0.00/0/30

Ship Via	Shipping and Handling Terms	LI-COR Consultant
UPS Ground	Prepaid & Add	Erik Johnson x3715

Item No.	Qty	Shipment ARO	Part No. and Product Description	Unit Price	Net Price	Price Extension
1	1	30 days	LI-7500A Open Path CO2/H2O Analyzer Includes: LI-7540 Open Path CO2/H2O Analyzer LI-7550 Analyzer Interface Unit	$17,800.00	$17,800.00	$17,800.00
2	1	30 days	7900-720 Satellite Communication System Satellite Communication System for use with LI-COR Eddy Covariance System. Includes antenna, Hughes modem, necessary cables, and mounting box with hardware. For tall tower operations, the 50 meter Turck to Turck ethernet cable (392-14103) is required.	$2,275.00	$2,275.00	$2,275.00
3	1	30 days	7900-340 Analyzer Mounting Kit	$70.00	$70.00	$70.00
4	1	30 days	7900-342 Crossover Fitting	$25.00	$25.00	$25.00
5	1	30 days	**Option:** GILL-WMP Gill WindMaster Pro Sonic Anemometer Omni-directional anemometer with wind speed range of 0-65 m/s and standard output rate of 32Hz. Instrument is calibrated and includes: Carrying case Mount Serial communication cable and analog outputs	$7,000.00	$7,000.00	$7,000.00

Page 1 of 2

Item No.	Qty	Shipment ARO	Part No. and Product Description	Unit Price	Net Price	Price Extension
6	1	30 days	**Option:** 9975-033 Cable Windmaster to 7550	$300.00	$300.00	$300.00

Comments

Shipping charges are an estimate and subject to change.

Subtotal	$27,470.00
Total Price	$27,470.00
Shipping and Handling (est.)*	$100.00
Grand Total	**$27,570.00**

Terms and Conditions

Refer to Quote when placing order.

LI-COR Standard Terms and Conditions of Sale and Warranty can be viewed at: http://www.licor.com/corp/terms_conditions.html

Visit us online at http://envcatalog.licor.com, or Email order to envsales@licor.com or FAX Order to 402-467-2819 ATTENTION SALES DEPARTMENT

ALL PRICES: Are in US DOLLARS and are exclusive of any import duties, customs clearance fees and/or international local taxes.

U.S. SALES TAX: *LI-COR is required to charge tax in the following states: CA, FL, GA, HI**, ID, IL, IN, IA, MD, MA, MI, MN, MO, NE, NJ, NY, NC, OH, PA, SC, TX, UT, VA, WA, WI. If you are tax exempt, a copy of your tax exemption certificate will be required prior to placing the order, otherwise tax will be charged to your final invoice. **Special note – for the State of Hawaii a 4% excise tax will be added to the total price.

PRICES AND WARRANTY: Valid only for final destinations in the USA, CANADA, AND MEXICO.

SPECIFICATIONS: As per LI-COR literature

MADE IN USA

Appendix F

Sensitivity Analysis for SSEBop

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An exercise to analyze the sensitivity of SSEBop to different input databases and parameterizations was undertaken by David W. Eckhardt of the U.S. Bureau of Reclamation (USBR), Denver office. This analysis was accomplished by executing five different runs of the SSEBop model using different *c*-factor calculations, number of processed satellite images, gridded T_{max} datasets, and ground-based meteorological data (Table F-1). Note that due to differences in the method used to calculate *c*-factors and the differing input datasets used, the results published in this appendix are distinct from the U.S. Geological Survey (USGS) SSEBop results described in the main body of this report. USBR ported the USGS SSEBop model from Python script to the ERDAS Imagine processing environment in which all processing reported in this appendix occurred.

Table F-1 Variations of SSEBop applied in sensitivity analysis

Designation	Number of Scenes	Weather Station	T_{max} Database	*c*-Factor
SSEBop (USBR-1)	16	Olathe 2	U of Idaho METData	Manual - HEI cold pixel
SSEBop (USBR-2)	16	Olathe 2	U of Idaho METData	Automated - Ag lands
SSEBop (USBR-3)	18	Olathe 2	U of Idaho METData	Automated - Ag lands
SSEBop (USBR-4)	18	Olathe 2	Daymet	Automated - Ag lands
SSEBop (USBR-5)	18	Olathe 1	Daymet	Automated - Ag lands

c-factors were calculated in two different ways. Four of the model runs labeled SSEBop (USBR-2, -3, -4, and -5) in Table F-1 used the statistical method described in the main body of this report to determine the *c*-factor, with one major difference. Instead of following the USGS protocol in which statistics calculated from the entire Landsat scene are used to estimate the *c*-factor, statistics were calculated using only pixels which fell within agricultural areas identified in the shapefile provided by Wilson Water Group. One model run labeled SSEBop (USBR-1) made use of a manually-selected *c*-factor which produced an *ETrF* of 1.05 at the cold pixel selected for the R-METRIC analyses.

Two different image sets were selected for processing by USBR, which chose to process 16 images, and the USGS which chose to process 18 images. The difference arose from judgement calls relating to the benefit of adding another snapshot in time to improve the characterization of vegetation development, versus the cost associated with using images that were acquired under sub-optimal conditions.

Two different gridded T_{max} datasets were investigated. The University of Idaho METData dataset produced daily T_{max} estimates at a 24 arc-second grid spacing. These data were available for download with a 1- to 2-day latency, so T_{max} data specific to individual days in 2015 were used in processing. The Daymet T_{max} data were long-term (approximately 30-year) daily averages. Both of these gridded T_{max} data sets were calibrated to daily maximum temperatures measured at a Colorado Agricultural Meteorological Network (CoAgMet) meteorological station (either Olathe 1 or Olathe 2).

The two different meteorological stations used in processing (Olathe 1 and Olathe 2) were separated by 3 kilometers (km), with an elevation difference of 40 meters (m). Jama Hamel from USBR's agricultural weather network (AgriMet) program performed quality control on the meteorological data from each station.

RESULTS

Comparison of Evapotranspiration (ET) Estimates with Colorado Eddy Covariance (EC) Tower

Figure F-1 shows a comparison of EC tower cumulative ET ground-truth data for the 2015 growing season along with the four SSEBop (USBR) results. With reference to Figure 4-1, R-METRIC produces the highest cumulative estimate, followed by SSEBop (USBR-1). The other three estimates (SSEBop [USBR-2, -3, and -4]) are quite similar to one another. All SSEBop (USBR) estimates are higher than the tower ET and lower than SSEBop (USGS) (data not shown).

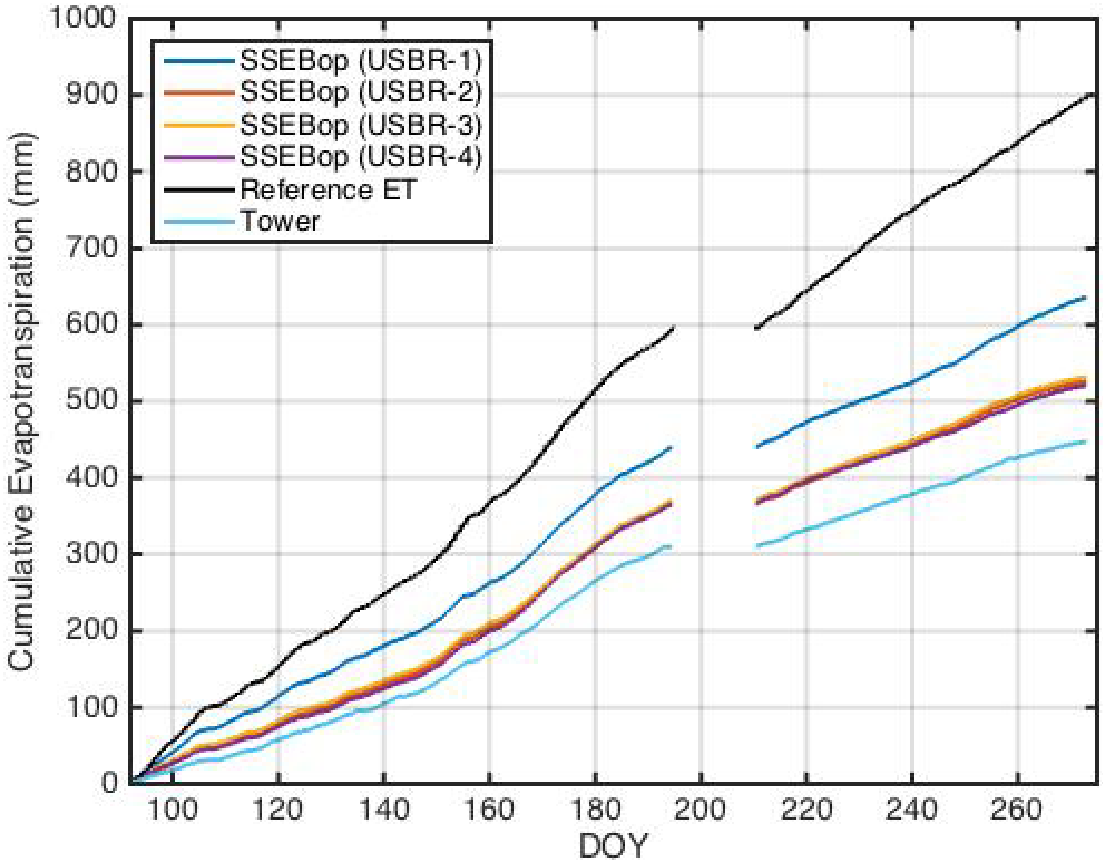

Figure F-1 Comparison of EC tower cumulative ET ground-truth data for the 2015 growing season with SSEBop (USBR) remote sensing methods; Penman-Monteith ET for a reference alfalfa surface using Olathe 2 weather station data is also plotted as an upper boundary condition, indicating the EC tower site near Rifle, Colorado, was under some water stress during the 2015 growing season

The linear least-squared error regression models predicting remotely sensed daily ET from ET measured at the EC tower generated from the 182 data points are presented in Table F-2. All methods have a positive intercept with the low value of 1.12 for SSEBop (USBR-4) and a high value of 1.83 for SSEBop (USBR-1). The slopes of the equations are similar, ranging from 0.76 for SSEBop (USBR-1 and -2) to 0.80 for SSEBop (USBR-4). Table F-2 also indicates the coefficient of determination for these methods and the root mean square error (RMSE). The *R*-

squared values are relatively low which is evidenced by the scatter of the data around the 1:1 line. The values of the RMSE range from a low of 0.90 millimeters per day (mm/d) for SSEBop (USBR-2) to a high value of 1.10 mm/d for SSEBop (USBR-1).

Table F-2 Linear regression analysis results for remote sensing methods used in sensitivity analysis vs EC tower measured daily ET for growing season

Remote Sensing Method	Linear Regression Equation	No. Data Pairs	*R*-squared	*RMSE* (mm/d)
SSEBop (USBR-1)	$ET_{rs} = 0.76\ (ET_{tower}) + 1.83$	182	0.44	1.10
SSEBop (USBR-2)	$ET_{rs} = 0.76\ (ET_{tower}) + 1.18$	182	0.55	0.90
SSEBop (USBR-4)	$ET_{rs} = 0.80\ (ET_{tower}) + 1.12$	182	0.51	1.01

In order to minimize the effects of interpolation, linear regression statistics were also calculated for just days of satellite overpass (Table F-3). The *R*-squared value is quite low for SSEBop (USBR-1) and much higher for SSEBop (USBR-2) and SSEBop (USBR-4). The *R*-squared values are increased for SSEBop (USBR-2) and SSEBop (USBR-4) as compared to the full-season data.

Table F-3 Linear regression analysis results for remote sensing methods vs EC tower measured daily ET on days of satellite overpass

Remote Sensing Method	Linear Regression Equation	No. Data Pairs	*R*-squared	*RMSE* (mm/d)
SSEBop (USBR-1)	$ET_{rs} = 0.72\ (ET_{tower}) + 2.54$	13	0.33	1.27
SSEBop (USBR-2)	$ET_{rs} = 0.87\ (ET_{tower}) + 1.25$	13	0.65	0.80
SSEBop (USBR-4)	$ET_{rs} = 1.06\ (ET_{tower}) + 0.45$	15	0.72	0.82

Results in Figure F-2 indicate SSEBop (USBR-1), which was run using a manual *c*-factor chosen to provide a cold pixel temperature consistent with that used in R-METRIC. Figure F-2 shows considerable scatter but the results generally fall above the 1:1 line indicating a higher ET estimate using this remote sensing method. The points corresponding to days of satellite overpass (shown in red) show a similar trend as the seasonal data with a distinct positive bias.

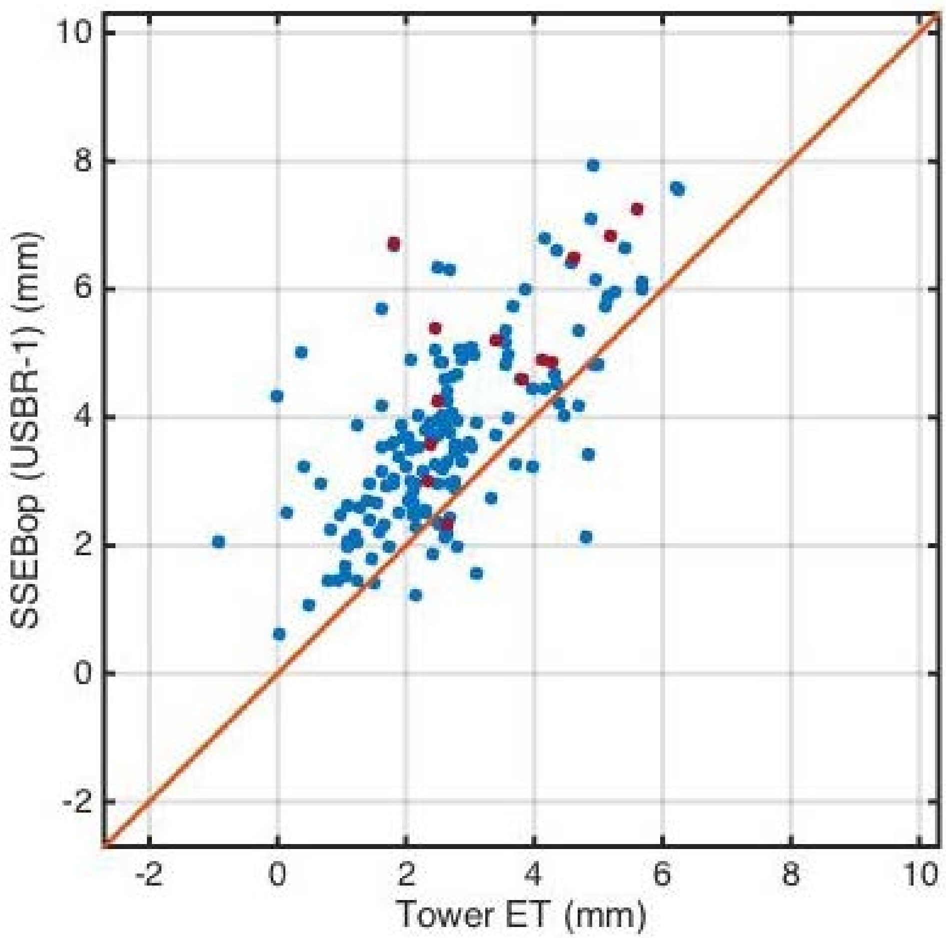

Figure F-2 Comparison of EC tower daily ET ground-truth data throughout the 2015 growing season with SSEBop (USBR-1) remote sensing estimated daily ET (1:1 line indicated in orange)

Comparison of Cumulative ET for Irrigated Lands: Colorado

Figures F-3, F-4, F-5, and F-6 demonstrate the differences produced by varied inputs to the SSEBop (USBR) methods. The manual *c*-factor, which was computed to be consistent with the ET estimated by the Hydrologic Engineering, Inc. (HEI)-selected cold pixel for R-METRIC, produces the greater magnitude of the two SSEBop (USBR) estimates (Figure F-3).

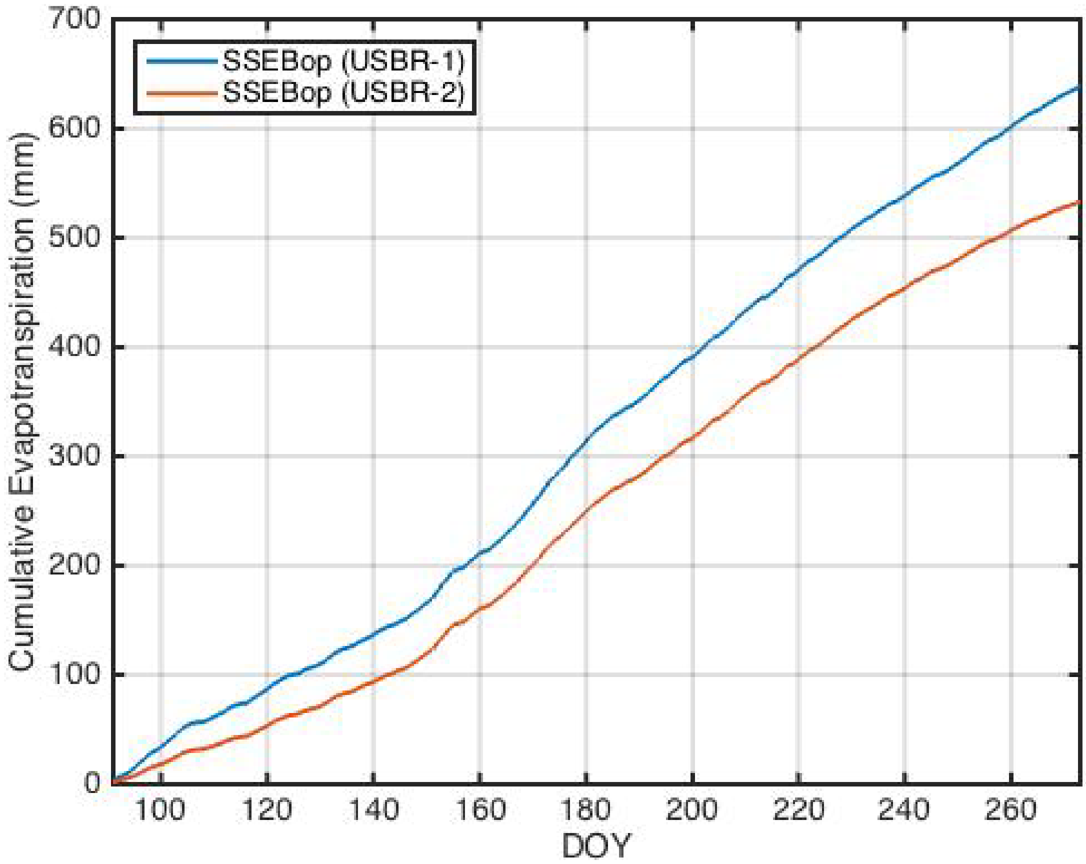

Figure F-3 Cumulative seasonal ET for the Colorado study area estimated using SSEBop (USBR-1) and SSEBop (USBR-2) remote sensing methods

Figure F-4 examines the impact of using a different number of Landsat scenes. The results show a difference of only 7 mm over the course of the growing season.

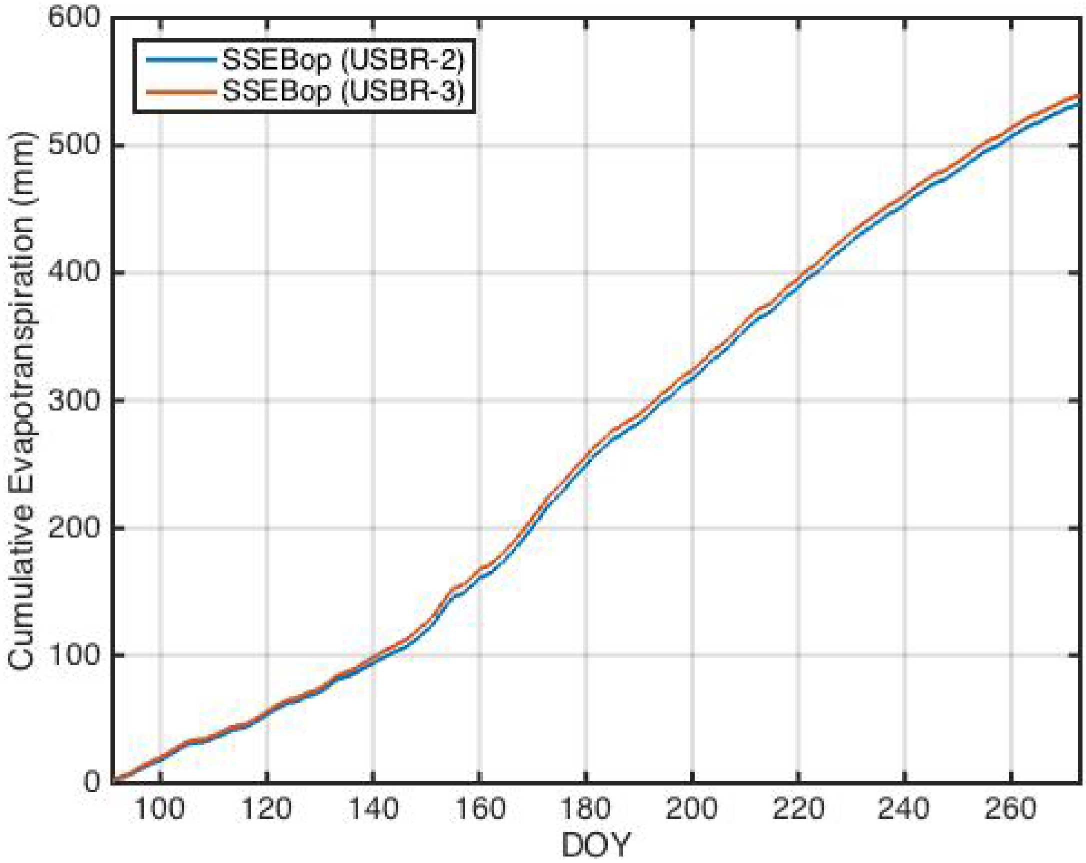

Figure F-4 Cumulative seasonal ET estimated for the Colorado study area using SSEBop (USBR-2) and SSEBop (USBR-3) remote sensing methods

Figure F-5 explores how using a different gridded T_{max} dataset can affect cumulative seasonal ET. Again, the estimates are similar, with the University of Idaho METData data set producing a greater estimate than the Daymet data set.

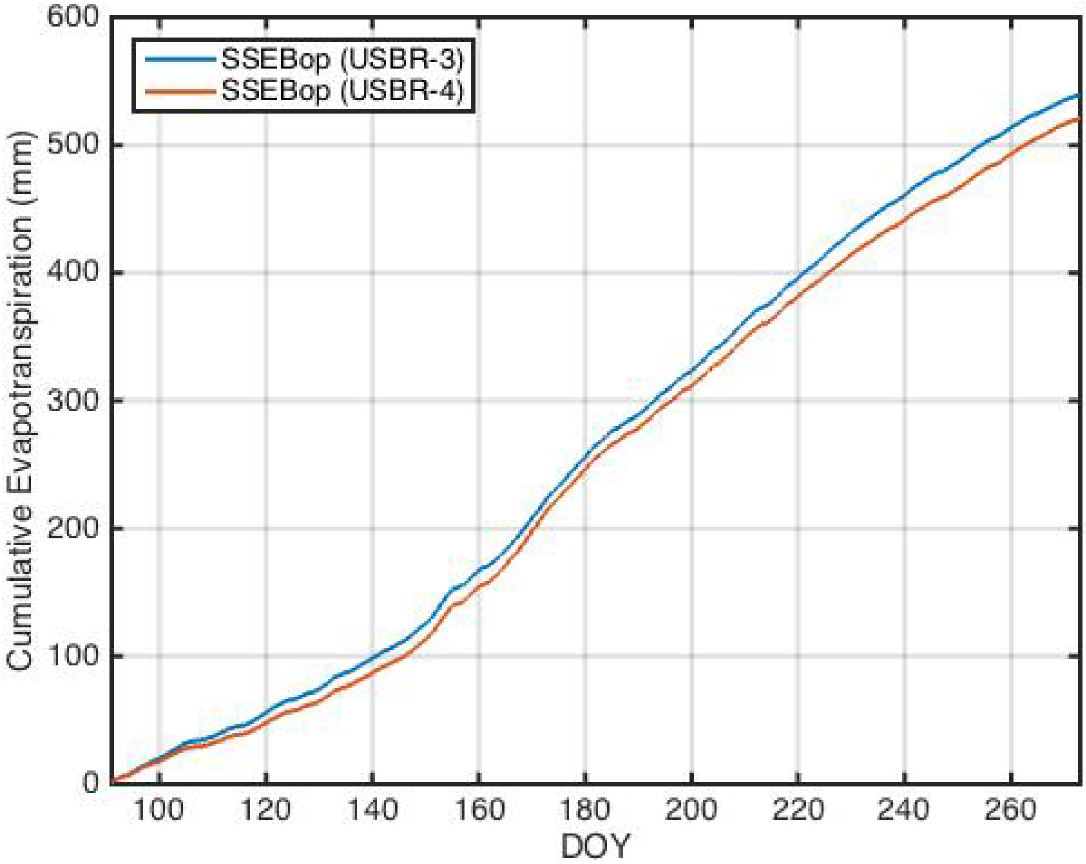

Figure F-5 Cumulative seasonal ET for the Colorado study area estimated using SSEBop (USBR-3) and SSEBop (USBR-4) remote sensing methods

Figure F-6 shows the difference in the ET estimate produced using reference ET from two different meteorological stations located approximately 3 km apart. The difference in seasonal reference ET (i.e., 473 mm using Olathe 1 and 521 mm using Olathe 2) is a bit surprising but points out the reality of field data collection. This difference could be caused by variations between sensors, solar radiation sensors being the most susceptible, and differences in station citing and exposure. Photographs of the Olathe 1 installation are available at http://www.colostate.edu/Orgs/Vegnet/COAGMETLOCATIONS.html, and indicate this is not an ideal site for reference ET data. This also supports the argument for standardized data quality control to be conducted throughout the growing season, sometimes by testing against portable, higher quality sensors which can be used to evaluate all stations in a network.

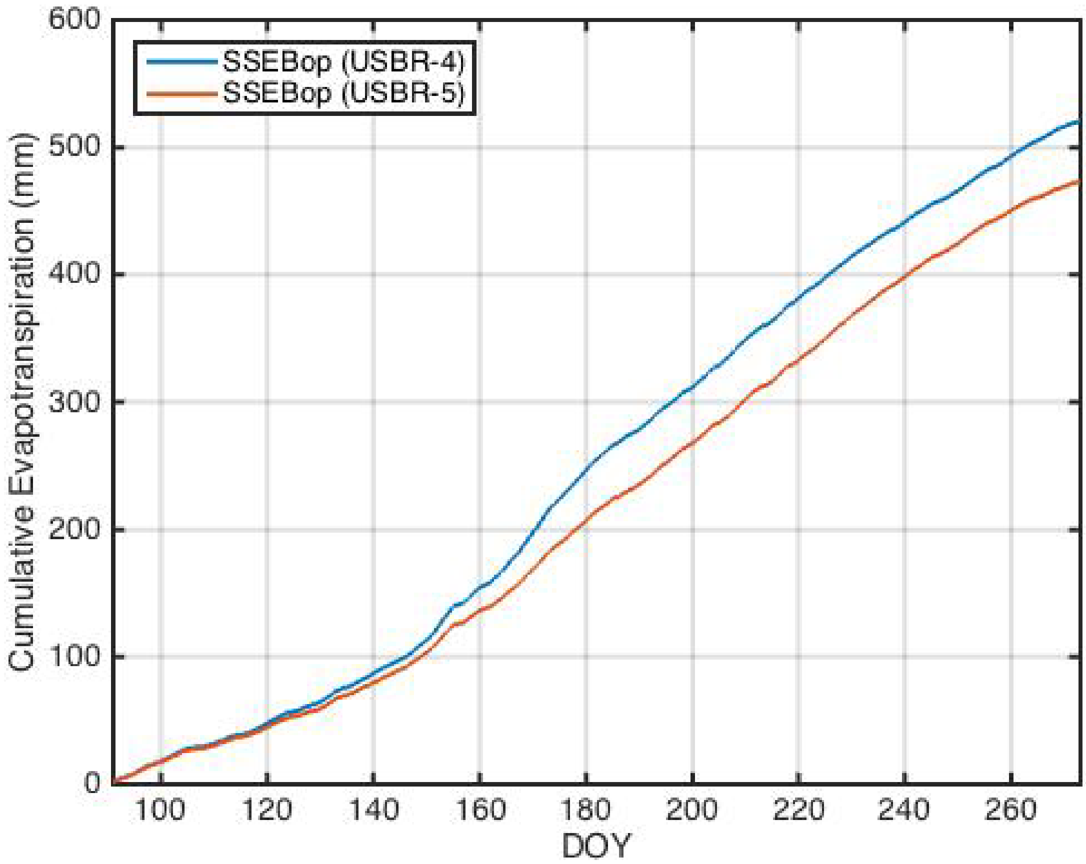

Figure F-6 Cumulative seasonal ET for the Colorado study area estimated using SSEBop (USBR-4) and SSEBop (USBR-5) remote sensing methods

From the results of these USBR runs, a few conclusions can be drawn.

1) Differing *c*-factors

As explained in the main body of this report, R-METRIC and SSEBop not only have significant differences in their internal algorithms, but they also differ in how they are calibrated to surface conditions. R-METRIC uses manually-selected hot and cold pixels to calibrate its sensible heat flux model. SSEBop links ET estimates directly to surface temperature values and uses an automatically-derived *c*-factor to estimate spatially-varying cold pixel temperatures (where *ETrF* = 1) from gridded maximum air temperature data. The SSEBop procedure then adds pre-defined *dT* values to those estimated cold pixel temperatures in order to define the 'hot pixel' temperatures (where *ETrF* = 0). Tables of results produced by R-METRIC and SSEBop demonstrate differences in model ET estimates, but not whether these differences came from the model algorithms themselves or from how the automated *c*-factor method approximated cold pixels selected by trained image analysts. Comparing R-METRIC results with SSEBop (USBR-1) in Figure F-1 shows that even when the *c*-factor multiplied by the gridded T_{max} value equaled the cold pixel temperature used in R-METRIC runs, R-METRIC produced seasonal ET estimates that were approximately 20 percent greater than those from SSEBop. Figures F-1 and F-3 also show a similar difference between SSEBop (USBR-1) and SSEBop (USBR-2), indicating that the automated *c*-factor selection method does not, in this case, replicate temperatures at the cold pixels manually selected by image analysts.

2) Differing T_{max} data sets

The two T_{max} data sets used in this analysis were quite different, with the University of Idaho METData depicting 2015 conditions, and the median Daymet data set depicting daily long-term average air temperatures. However, calibration of each T_{max} grid to T_{max} data measured at the same meteorological station effectively normalized the data sets to the point where they produced estimates that varied by only 3.4 percent (Figure F-5).

3) Differing meteorological stations

Figure F-6 illustrates how critical it is to only use data from properly sited meteorological stations in the estimation of ET. Although the data from both Olathe 1 and Olathe 2 went through the same quality assurance/quality check procedure and although they were separated by only about 3 km in distance and 40 m in elevation, using Olathe 1 for model calibration instead of Olathe 2 resulted in a 9 percent drop in estimated seasonal ET. (Note that Olathe 2 was used as the primary meteorological station for Colorado in this study based on regression analysis of reference ET from all available meteorological stations in the region.)

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