MAPPING STATEWIDE EVAPOTRANSPIRATION IN NEW MEXICO

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ABSTRACT

This project aims to find an evapotranspiration model that can be implemented across New Mexico in order to quantify the amount of water returning to the atmosphere from the land surface. Three evapotranspiration models, ALEXI, SSEBop, and MOD16, were analyzed in this study to test their accuracy against recorded field data from flux towers with Eddy Covariance systems. Each model returned different results and it provided a geographical location on where the model works more effectively and where it does not. Based on the linear regressions, SSEBop V3 performed with the most accuracy statewide. A search for an evapotranspiration / precipitation ratio was also conducted in areas where these two components should be close to equal. For precipitation estimates, PRISM data were used.

Keywords: Evapotranspiration, Models, ET, Flux Towers, Eddy Covariance systems, ET/P Ratio, MOD16, SSEBop, ALEXI, METRIC, New Mexico, HUC8, Water Planning Regions

Table of Contents

List of Maps, Figures, and Tables

LIST OF ACRONYMS

ALEXI………………………………………..	Atmospheric Land Exchange Inverse
ET………………………………………….	Evapotranspiration
GOES………………………………………	Geostationary Operational Environmental Satellite
JER…………………………………………	Jornada Experimental Range
LAI…………………………………………	Leaf Area Index
METRIC…………………………………...	Mapping Evapotranspiration at High Resolution with Internalized Calibration
MOD16…………………………………….	MODIS Evapotranspiration Global Algorithm
MODIS…………………………………….	Moderate-Resolution Imaging Spectroradiometer
NDVI………………………………………	Normalized Difference Vegetation Index
NOAA……………………………………...	National Ocean and Atmospheric Administration
P……………………………………………	Precipitation
PRISM……………………………………..	Parameter-elevation Relationships on Independent Slopes Model
SSEBop……………………………………	Simplified Surface Energy Balance
TSEB………………………………………	Two-Source Energy Balance
USDA……………………………………...	United States Department of Agriculture
USGS……………………………………....	United States Geological Survey
VIIRS………………………………........	Visible Infrared Imaging Radiometer Suite

1. Introduction

Water has been one of the main driving forces of expansion in the American Southwest for over a century. This essential compound has allowed urban centers, populations, and even agricultural areas to expand in places where it was once thought impossible. Most of the water that the American Southwest receives originates from two sources; rivers and precipitation. In a water budget created for the Arroyo Seco watershed situated in California; precipitation and evapotranspiration (ET) were the biggest components in that study area [Brick 2010]. Knowing that ET and precipitation are the biggest components of water budgets, this project aims to find an operational evapotranspiration model that is accurate and reliable for the entire state of New Mexico which could be incorporated into a statewide water budget.

Evapotranspiration is the total sum of transpiration (water transpiring from vegetation canopies) and evaporation (water evaporating from the land surface) that occurs on a daily basis with varying degrees across different biomes and ecosystems. New Mexico, due to its large spatial area (315,194 km^2) has multiple biomes, which in turn cause different rates and ranges of ET across space-time. It is crucial to know the rate of ET since it is the largest water loss for the state on the order of the precipitation input. Increasing water demand due to a growing population and industry increases pressure on all sectors of society and the natural environment by creating unbalanced water budgets, which then create higher risks of crop failure, faster depletion rates of underwater aquifers, complications with irrigation scheduling, accelerated rates of soil erosion, and even alter the migration patterns of natural species. Knowing and understanding how much water is leaving the surface and canopy back into the atmosphere allows water managers, hydrologists, and farmers plan a strategy to mitigate risks associated with drought as well as water shortages.

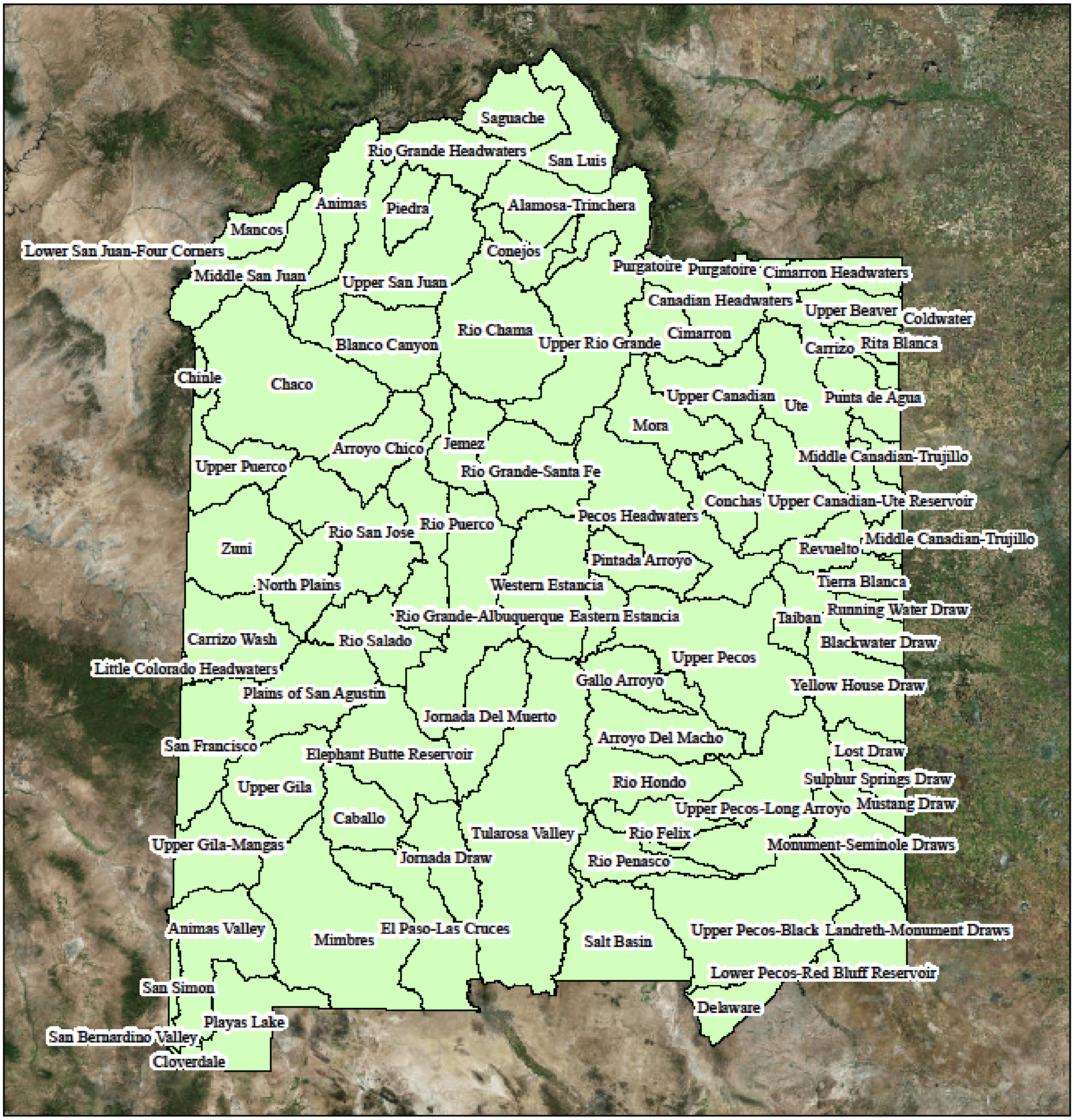
This project used three different models for quantifying ET and each of the three different models produced different results. The three models of quantifying ET are the following:

- ALEXI V7 – Atmospheric Land Exchange Inverse Model from the USDA, Agricultural Research Service, and NOAA, Office of Satellite and Product Operations
- MOD16 – MODIS Global ET Algorithm from The University of Montana
- SSEBop V3 – Simplified Surface Energy Balance from the USGS, Earth Resources Observation Systems Data Center

To obtain precipitation estimates, PRISM data were acquired from Oregon State University Climate Group. The data were verified with rain gauges scattered across New Mexico and the modeled values had a good correlation with observed values. METRIC (another ET model) data were acquired for the purpose of validation of the three models used for quantification of ET. However, due to uncertainties, METRIC data were not used. Eddy Covariance Flux tower data were used for validation of the three models. Yearly time series were created for each individual model using a color stretch that obtained its maximum and minimum values from the model that performed the best. For a more detailed analysis of how each model performed, refer to section 4 of this paper.

The data of both ET and precipitation were then processed using ArcGIS in order to develop monthly and annual averages and totals across New Mexico Water Planning Regions, watersheds (based on the HUC-8 digit code assigned by the USGS), and counties. As this study progressed, models were constantly updated by their creators, therefore this analysis presents the latest models. This study looked at the three different models used for evapotranspiration, their problems, and accuracy against field measured data. A search for an ET / precipitation ratio was also conducted using the model with the greatest yearly accuracy. Since the Rio Grande headwaters are in Colorado, the extent of this project exceeded the New Mexico-Colorado state line. However, when quantifying ET, the boundaries were set at the political border of New Mexico, see section 2.4.

Map 1: Defining the Study Area



This map depicts the study area used in the Evapotranspiration part of the Statewide Water Assesment. Since the Rio Grande is a major source of water for New Mexico, its headwaters are included in the study area.

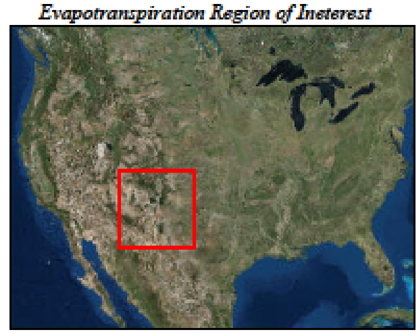
Imagery Source: ESRI, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/ Airbus DS, USDA, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

Map Created by: Francisco Ochoa
Date: 6/21/2016
Coordinate System: UTM Zone 13N
Datum: NAD 1983

0 75 150 Km

Watersheds (HUC-8)

Evapotranspiration Region of Ineterest



2. Acquisition of Evapotranspiration Models

2.1 Atmospheric Land Exchange Inverse Model (ALEXI)

The Atmospheric Land Exchange Inverse Model (ALEXI) is an evapotranspiration model developed by the USDA, Agricultural Research Division in collaboration with NOAA, Office of Satellite and Product Operations. The origin of this model is based on the Two-Source Energy Balance Model (TSEB) developed in 1995 by Norman and Kustas. This model is based on remote sensing observations, thermal bands, land cover and surface environmental properties. Its units are reported in mm/day. Advantages of using this model are that it separates vegetable and soil components, there are high ET spatial patterns, and this model tends to favor mountains and areas of high vegetation. ALEXI requires the following input data to calculate ET:

1. Surface Radiometric Temperature from Geosynchronous Satellites
2. Surface and Upper Air Wind Speed
3. Surface and Upper Air Temperature
4. Leaf Area Index, Vegetation Cover
5. Canopy Characteristics from Land Surface Classifications
6. Downwelling Solar Radiation
7. Soil Properties from STATSGO

However, its disadvantages are that it is produced in a coarse spatial resolution of 4 km by 4 km, the output grids have many null values that require filling, it reports extreme values of ET during a dry year, and it is produced in daily grids, which requires time and expertise to aggregate daily data to a monthly and yearly scale. This model was analyzed from 2000-2013 for the entire study area using ALEXI V6 and from 2003-2014 using ALEXI V7, both different versions of the model. This analysis will focus on ALEXI V7 since it is the latest version of this model. Section 2.1.1 shows the equations used to calculate actual ET using ALEXI.

2.1.1 Calculating ET with ALEXI

ALEXI calculates ET using a surface energy balance (equation 1) based on the total amount of solar energy available at the land surface on a daily basis. In equation 1, Rn corresponds to incoming net radiation, G represents the soil heat flux, H represents the sensible heat flux, and λE is the latent heat of evapotranspiration.

$$(1)\ \lambda E = Rn - G - H$$

However, ALEXI incorporates into its calculations of these individual components a Two-Source Energy Balance approach (TSEB; equation 2). The TSEB partitions the surface energy balance equation into canopy and surface readings. The following list shows variables from equation 1 that get partitioned.

- $Rn = RN_s + RN_c$
- $H = H_s + H_c$
- $\lambda E = \lambda E_s + \lambda E_c$

$$(2)\ T_{\mathrm{RAD}} \approx f(\theta)T_c + [1 - f(\theta)]\,T_s$$

The use of the TSEB is implemented in ALEXI to detect stress in the canopy and soil by using a time rate of change from GOES surface temperature [Anderson et al 2007]. T_s and T_c, both correspond to canopy and surface radiometric temperature extracted from GOES satellite data, which aids in reducing bias across continental scales. Using equation 2, the TSEB, users can calculate different components of equation 1 from observed radiometric temperature. Since the soil heat flux is only part of the land surface and not found in canopies, ALEXI does not partition this component. In equation 2,T_{RAD} represents radiometric temperature observed from geostationary satellites, which have a very high temporal resolution of 30 minutes but a coarser spatial resolution. The variable $f(\theta)$ signifies fractional cover, which can be calculated in the following manner:

$$(3)\ f(\theta) = 1 - exp\left(\frac{-0.5\Omega(\theta)F}{\cos\theta}\right)$$

Where θ represents the satellite viewing angle, F corresponds to the Leaf Area Index from MODIS satellites, and $\Omega(\theta)$ is the vegetation clumping factor. A smaller Ω value, indicates vegetation clumping while a Ω value closer to 1 indicates random dispersion [Anderson et al., 2005]. After obtaining both canopy and surface temperature, one can solve for the respective components of equation 1 separately using the following equations.

$$(4)\ G = \alpha_g RN_s$$

$$(5)\ H_s = \rho c_p \frac{T_s - T_{AC}}{R_s}$$

$$(6)\ RN_s = (L_d - L_{u,s}) + (S_{d,s} - S_{u,s})$$

$$(7)\ RN_c = H_c + \lambda E_c$$

$$(8)\ H_c = \rho c_p \frac{T_c - T_{AC}}{R_x}$$

To calculate G, the soil heat flux (equation 5), ALEXI assumes that this component is a fraction equal to 0.31 of the total surface net radiation, RN_s [Anderson et al 2007].

2.2 Simplified Surface Energy Balance Model (SSEBop)

The Simplified Surface Energy Balance (SSEBop) is an ET model developed by the USGS, Earth Resources Observation Systems Data Center, and Dr. Gabriel Senay. This model is based on remote sensing observations, temperature, and Reference Evapotranspiration (ETo), its units being reported in mm/day. Several advantages of using this model are that its end product bears a fine spatial resolution of 863m by 863m (having this small spatial resolution takes into account spatial variability of the surface), it uses thermal bands meaning that the model can be implemented with Landsat or MODIS Imagery. It does not take into account the soil heat flux as most ET models do, and it requires a small list of input variables to calculate actual ET. The following list is the input data required to calculate actual ET using SSEBop:

1. 8 Day Composite Satellite Observed Surface Temperature
2. Air Temperature Grids
3. Reference Evapotranspiration
4. NDVI – Normalized Difference Vegetation Index

However, there are also some disadvantages that come with this model, such as the accuracy of the input variables and the high ET values during dry years. Regardless of these disadvantages, ET data of this model were obtained from 2000-2014 for the entire study area, analyzed and validated with field observations of ET. It was then mapped into a time series for data visualization. Results indicated that this model performs well with recorded field observations. In order to achieve better results, certain implementations must be done to this model. Section 2.2.1 breaks down the ET calculations for the SSEBop.

2.2.1 Calculating ET with SSEBop

In order to successfully quantify ET, the SSEBop model establishes and calculates ET using hot and cold pixels. These pixels are places on the Earth where actual ET is taking place (hot) and places where it is not (cold). Using this approach is analogous to using a wet bulb-dry bulb method when calculating dew point temperature. By using this simple approach in the SSEBop, ET now becomes a function of land surface temperature and ETo [Senay et al 2013]. The ETo is used to provide reference ET estimates and to scale up / down actual ET derived from the model. The following equations describes the necessary steps to calculate actual ET using the SSEBop model.

First, a temperature coefficient, equation 9, (c) is needed as well as predefined temperature difference function, equation 10 (Dt).

$$(9)\ c = \frac{Ts\_Cold}{Ta} \qquad (10)\ Dt = \frac{Rn * Rah}{Pa * Cp}$$

In equation (9), Ts_Cold represents a satellite based surface temperature reading at a cold pixel, where NDVI is greater than or equal to 0.8 and Ta represents air temperature. NDVI is a unit less ratio with values ranging from -1 to 1 and it is calculated by using the red and near infrared bands values from remote sensing satellites. In equation (10), (Dt) is a product of net radiation (Rn) and the aerodynamic resistance to heat (Rah) divided by the product of air density (Pa) and the specific heat of air at constant pressure (Cp). These two equations, c and Dt (equation 9 and 10), are required to establish a cold boundary condition (Tc) and a hot boundary condition (Th). The equations to calculate both conditions are the following:

$$(11)\quad Tc = c * Ta \qquad (12)\ Th = Tc * Dt$$

The cold boundary condition (Tc), equation 11, is a product of air temperature (Ta) and of the temperature correction coefficient (c), equation 9. In order to calculate the hot boundary condition, (Th), Tc must be calculated first as Th is a function of (Tc) and (Dt), equation 11 and 10 respectively. These two boundary conditions are then integrated into an ET fraction equation (ETf), which can be calculated in the following manner:

$$(13)\ ETf = \frac{Th - Ts}{Th - Tc}$$

In equation 13, Th and Tc (equations 12 and 11), are hot and cold boundary conditions in their respective order. A different variable is incorporated into equation 13, Ts, which represents satellite observed surface temperature in degrees kelvin. Land surface temperature is derived from observed radiances at the satellite. Finally, to calculate actual ET, ETf, equation 13 is inserted into the following function:

$$(14)\ ET = ETf * (K * ETo)$$

In equation 14, ETo is a gridded reference ET product, K is a crop coefficient equal to 1.2, and ETf is the ET fraction, calculated in equation 13.

2.3 MODIS ET Global Algorithm (MOD16)

MOD16 is the MODIS ET Global Algorithm derived from the MODIS *terra* and *aqua* satellites that provide daily coverage of the earth. This algorithm is an altered equation based on the Penman-Monteith method of calculating ET. Having this daily temporal resolution from the satellites led to the creation of this global ET product by The University of Montana's Numerical Terradynamic Simulation Group. Several advantages that this model has is that it emanates in a very fine resolution of approximately 1 km by 1 km, and this high ET spatial patterns tend to favor mountainous areas. In order to calculate ET using this algorithm, the following components are required [Mu et al., 2013].

1. Global Modeling Assimilation Office (GMAO) Daily Meteorological Data
2. MERRA GMAO Daily Metrological Data
3. Surface Albedo from MODIS and VIIRS Satellites
4. Land Cover from MODIS and VIIRS Satellites
5. Leaf Area Index (LAI) from MODIS and VIIRS Satellites
6. Fractional Photosynthetically Active Radiation from MODIS and VIIRS Satellites

The principal disadvantages that this model demonstrates are its many null values that require data filling and its spatial patterns show poor variation across southern New Mexico (see Map 4). Its histogram is also spiked with many low values, however, the biggest drawback was that it predicted very low values compared to the other models. Data were acquired from this model and analyzed from 2000 to 2013. When comparing the model to actual field observations, this model did not perform well as it showed very low yearly r^2 values.

Calculating ET using the MOD16 algorithm is very complex. Daily ET (λE) is the sum of daily ET from the wet canopy (λE_{wet_c}), the transpiration from the dry canopy surface (λE_{trans}) and the evaporation originating from the land surface (λE_{SOIL}). The following equations are used to calculate ET, for a more detailed explanation of the variables refer to [Mu et al., 2013]:

(15) $\lambda E = \lambda E_{wet_c} + \lambda E_{trans} + \lambda E_{SOIL}$

(16) $\lambda E_{wet_c} = \frac{(S * A_c + p * C_p * (e_{sat} - e) * F_c / rhrc) * F_{wet}}{s + \frac{P_a * C_p * rvc}{\lambda * \varepsilon * rhrc}}$

(17) $\lambda E_{trans} = \frac{(S * A_c + p * C_p * (e_{sat} - e) * F_c / r_a) * (1 - F_{wet})}{s + \gamma * (1 + r_s / r_a)}$

(18) $\lambda E_{SOIL} = \lambda E_{wet\_SOIL} + \lambda E_{SOIL_{POT}} * \left(\frac{RH}{100}\right)^{VPD/\beta}$

2.4 Quantification of Statewide Evapotranspiration

During the initial analysis of these three models, quantification of actual ET as a volume, simple statistics such as pixel count, and the mean was calculated for each model. From the total yearly volume, a component mean of 100.80 million acre-feet/year was discovered in New Mexico. This was done using the spatial resolution of each model multiplied by the actual pixel value (a recording of water by depth), returning a volume. However, to convert to acre-feet, one must first convert these ET values of mm/day to m^3 and then multiply by 1233.480209692.

Figure 3, shows the results for each different model compared to one another in yearly volumes of millions of acre-feet for just New Mexico. Results of these statistics indicate that ALEXI V7 over predicted ET values by a range of 79 % above the component mean. MOD16 and SSEBop V3 greatly under-predicted ET by 55% and 24% from the component mean. With these results, field validation procedures began to see how these three models perform against actual field observations of ET.

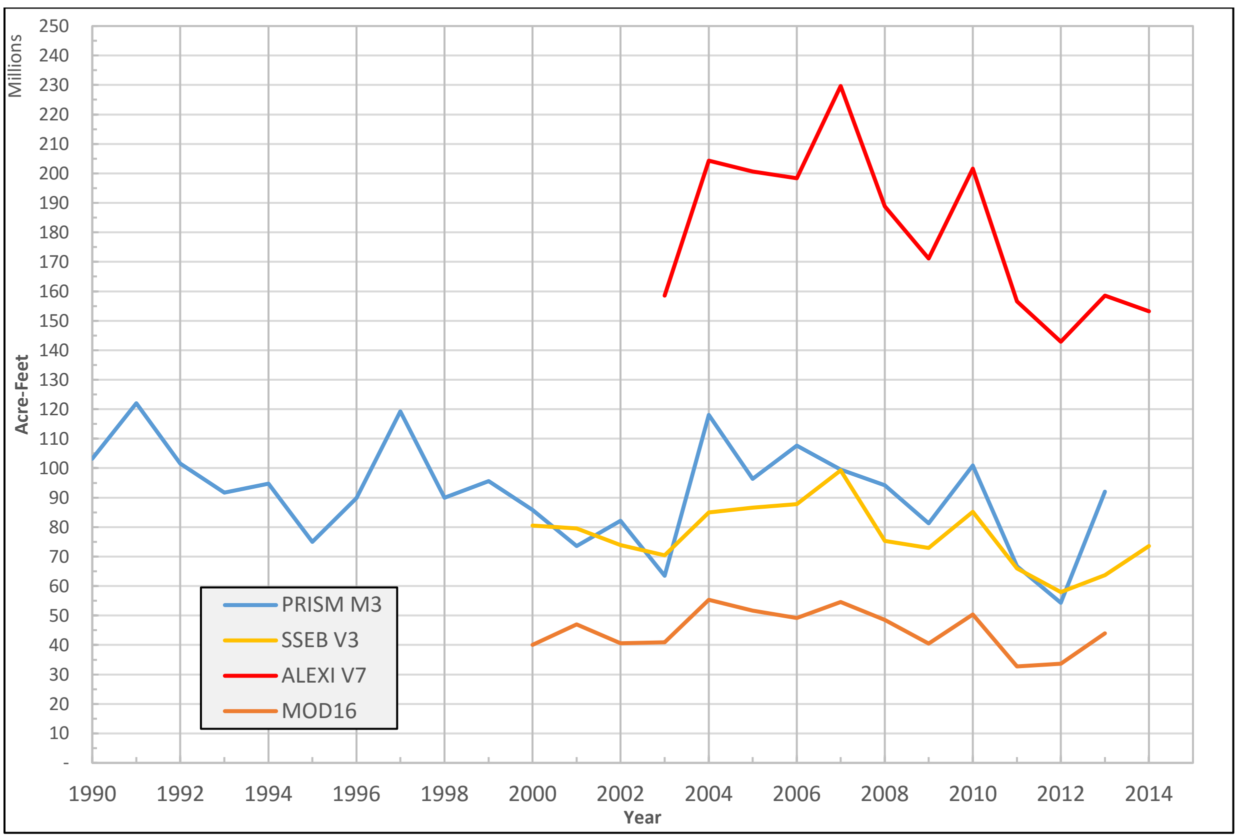


Figure 1: Yearly Statewide Comparison of Latest ET Models

Table 1: ET Models Yearly Components

Evapotranspiration Components			
Year	**ALEXI V7**	**MOD16**	**SSEBop V3**
2000	No Data	40.07	80.54
2001	No Data	47.01	79.49
2002	No Data	40.56	73.94
2003	158.52	40.89	70.44
2004	204.36	55.34	84.94
2005	200.66	51.66	86.56
2006	198.38	49.17	87.80
2007	229.65	54.62	99.24
2008	188.85	48.50	75.32
2009	171.12	40.43	72.91
2010	201.58	50.35	85.14
2011	156.56	32.73	65.97
2012	142.90	33.60	57.95
2013	158.56	43.97	63.72
2014	153.27	No Data	73.52
Mean (2000-2013)	180.37	44.92	77.17
Component Mean		**100.82**	
Mean Difference	79 % Higher	55 % Lower	24 % Lower
Cell Count	18427	414268	381265
Temporal Resolution	Daily	Monthly	Monthly
Approx. Spatial Resolution	≈ 4000 meters	≈ 1000 meters	≈ 1000 meters
Units	mm/day	mm/month	mm/month
Creator	USDA, Agricultural Research Service, NOAA, Office of Satellite and Product Operations	University of Montana, Numerical Terradynamic Simulation Group EROS Data Center	USGS, Earth Resources Observation Systems Data Center
Abbreviation	Atmosphere-Land Exchange Inverse Model	MODIS Global Evapotranspiration Algorithm	Simplified Surface Energy Balance Model
Color Code for Chart		Values in Millions of Acre Feet	
	Wet Year		Dry Year
	Third to Highest Volume		Third to Lowest Volume
	Second to Highest Volume		Second to Lowest Volume
	Highest Volume		Lowest Volume

Note: These values represent the latest versions of ALEXI, SSEBop, and MOD16.

2.5 Mapping Evapotranspiration with Internalized Calibration (METRIC)

Mapping Evapotranspiration at High Resolution with Internalized Calibration (METRIC) is an ET model developed by The University of Idaho that uses a standard energy balance equation, equation 1, to calculate actual ET. This model was employed by Dr. Jan Hendcrickx across the Middle Rio Grande area in New Mexico to validate ALEXI, SSEBop, and MOD16. METRIC returned various ET estimates in certain areas due to the spatial variability of New Mexico. Since the calibration of this ET model is based on individual satellite images, using this model for a large spatial area or simply using various images may introduce errors. Results indicated that ET was lower during the summer months and higher during the winter months, while in nature the opposite is observed. The model worked well in riparian corridors located along the Middle Rio Grande. Data, from a flux tower located in a riparian area in 2005, Bosque Salt Cedar, indicated that there was a very good agreement between observed values and modeled values. This linear regression returned a r^2 value of 0.89. METRIC also seemed to have good accuracy in the mountainous areas, r^2 values were 0.88 and 0.80 at both Valles Caldera flux stations.

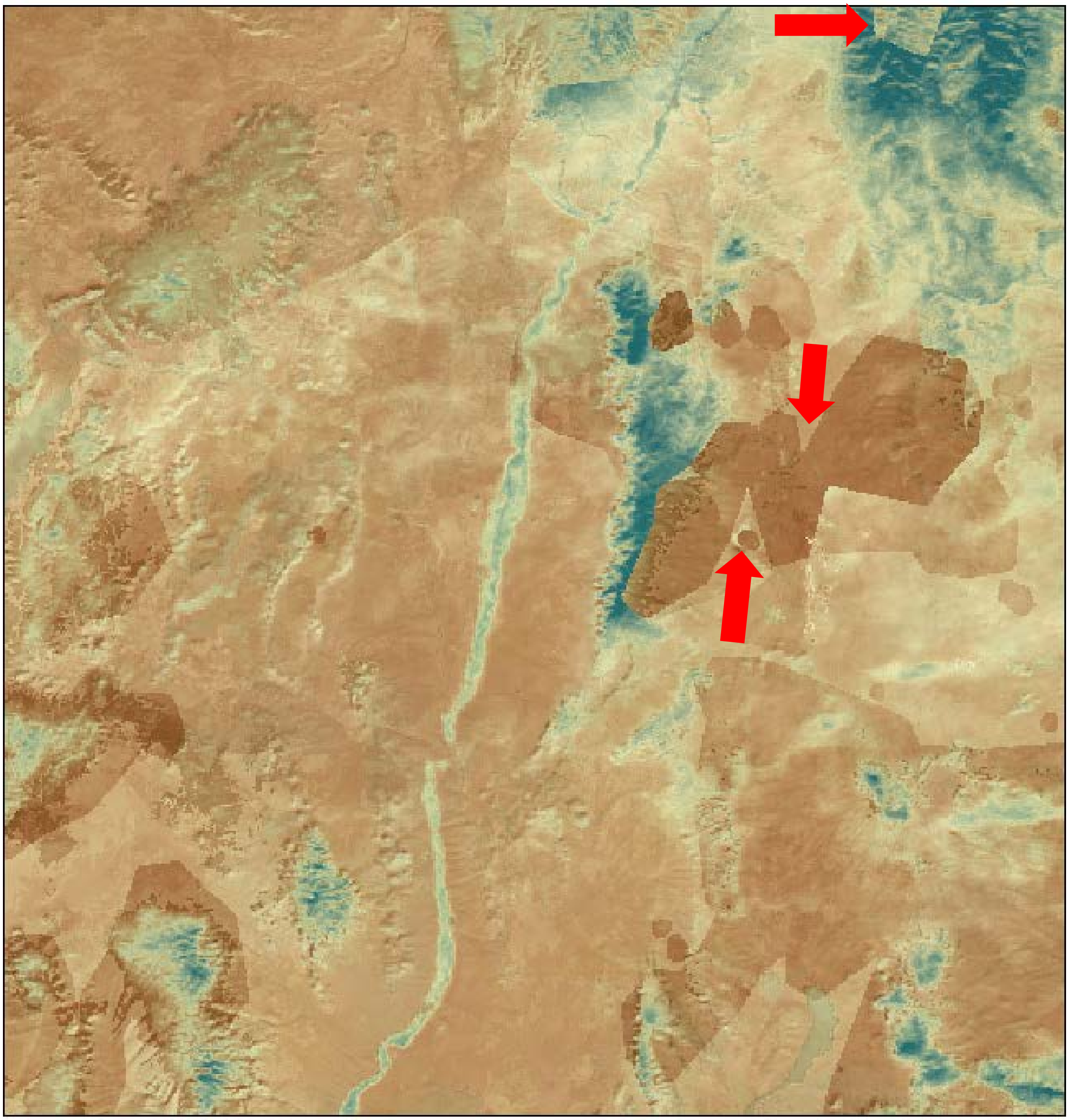
Figure 2 depicts a comparison of Bosque Salt Cedar's values with surrounding pixel values extracted from METRIC. An issue facing this model is that it loses spatial variability of the terrain and it creates non-natural features with its predicted values. Map 2 highlights with red arrows the non-natural features that are created across the landscape. Non-natural features like straight lines, polygons, and lines can be seen on the map. Due to the fact that this model only works well in riparian areas and the creation of non-natural features, this model would undergo further analysis before it is used to validate other ET products.

Table 2: METRIC Monthly Regression Results

Flux Station	Vegetation	Year	R^2
Bosque	Salt Cedar	2005	0.89
Valles Caldera	Evergreen/ Ponderosa Pine Forest	2007	0.88
Valles Caldera	Evergreen/ Mixed Conifer Forest	2007	0.80
Sevilleta	Desert Shrubland	2007	0.77
Sevilleta	Desert Grassland	2007	0.31

Note: Only flux station data from 2005 and 2007 were used to validate METRIC. To see where these stations are situated, refer to Map 3.

Map 2: METRIC'S non-natural features



This map depicts the study area used by the METRIC ET model as part of the Evapotranspiration project of the Statewide Water Assesment. Note the not-natural features that are created by this model with red arrows. It is probable that this image was not atmospherically corrected before processing.

Map Created by: Francisco Ochoa
Date: 6/2/2016
Coordinate System: UTM Zone 13N
Datum: NAD 1983

Imagery Source: ESRI, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/ Airbus DS, USDA, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

Evapotranspiration Region of Ineterest

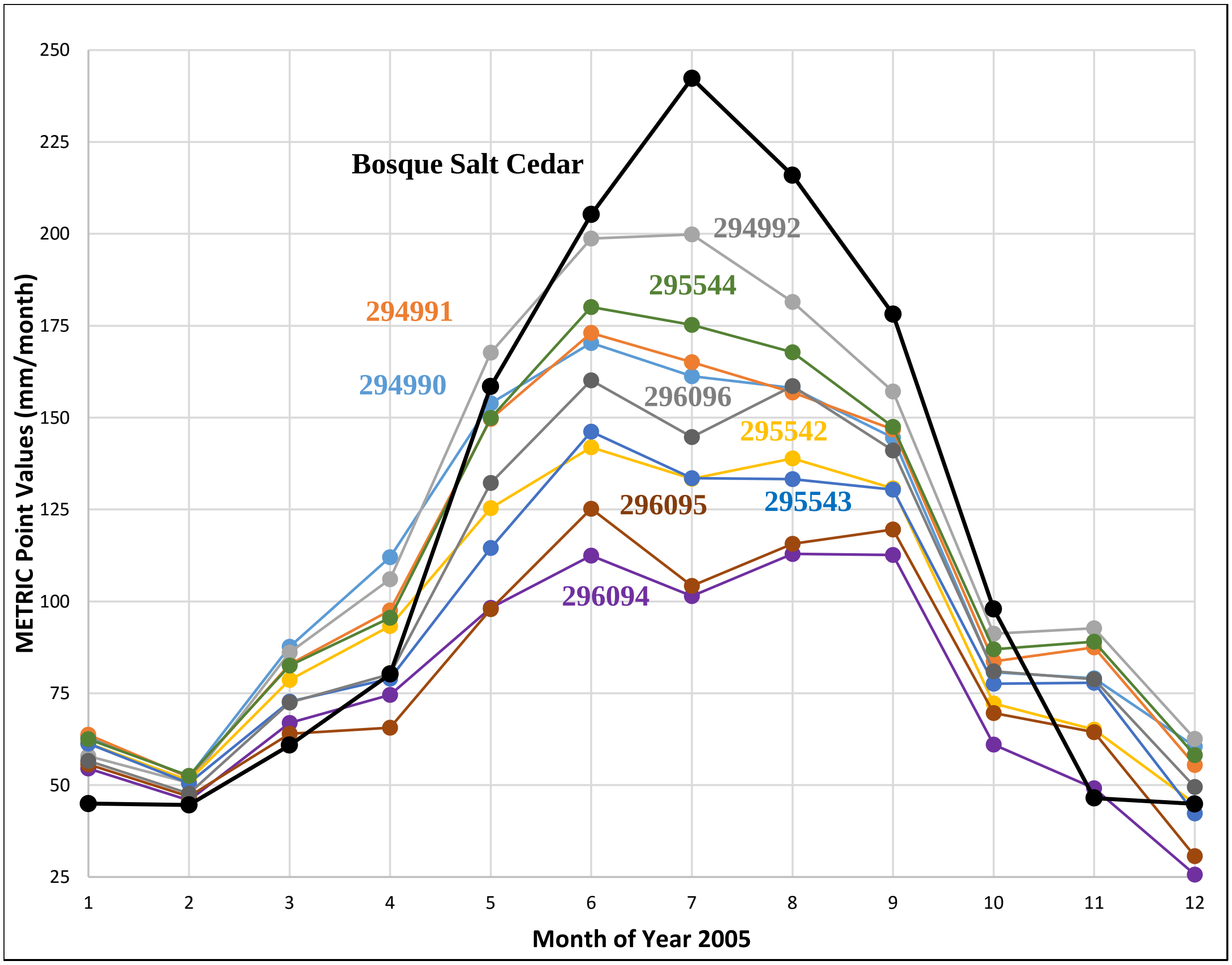


Figure 2: METRIC Performance with Bosque Salt Cedar Flux Station

3. Validation of Models

In order to find the accuracy of the different ET models under analyses, a comparison between modeled values and actual field measurements were made to validate the different models. Ameriflux is a network of monitoring stations that records several atmospheric processes such as precipitation events, wind speeds, and evapotranspiration using an Eddy Covariance system. New Mexico is host to several of these flux stations scattered in different ecological biomes. Map 3 depicts each flux station location. In order to evaluate the modeled ET results, the following steps were used.

1. Convert to point data the flux stations locations
2. Overlay gridded cells from respective models
3. *Extract By Points* the gridded cell that overlays on each individual point
4. Import data to Microsoft Excel and compare it to field data from stations

3.1 Eddy Covariance System Flux Towers in New Mexico

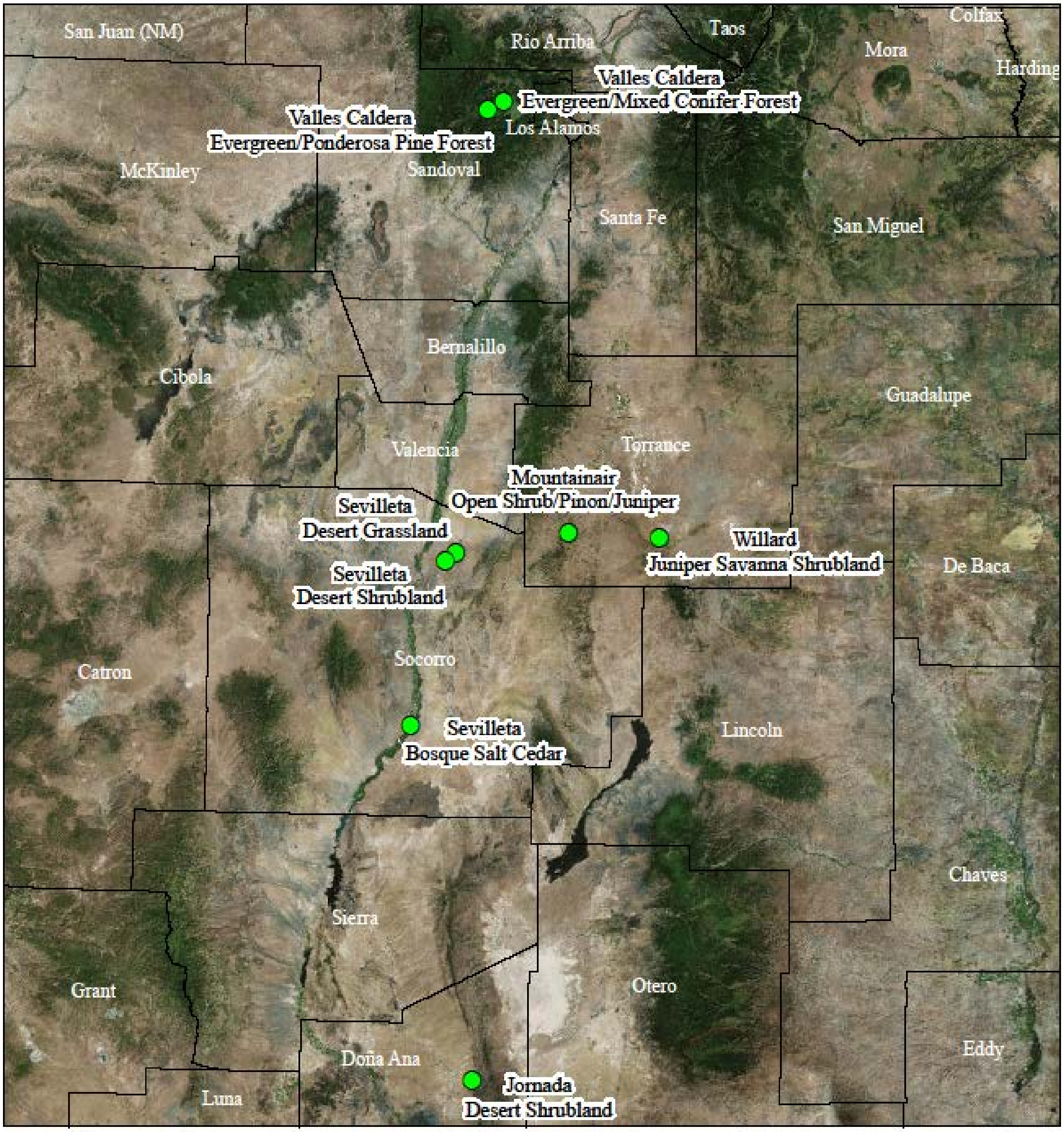
Data were obtained from each of the flux stations with Eddy Covariance systems situated in New Mexico from 2005-2011. In total, there were eight of these stations in the state. Six of these flux stations contribute to the Ameriflux Network operated by the Department of Energy, Office of Science. These stations are operated by Dr. Marcy Litvak from the Department of Biology at The University of New Mexico. Dr. Enrique Vivoni and his group from Arizona State University operated the flux tower situated in the Jornada Experimental Range. The flux tower labeled Bosque Salt Cedar located in the Sevilleta was operated by Dr. Salim Bawazir from the Department of Civil Engineering at New Mexico State University; this flux tower was only operational for the year 2005 and was situated in a riparian area. Data were acquired in half-hour intervals which required these readings to be converted into mm/day for each day of the Julian calendar year. After data was converted to mm/day, it was then aggregated into monthly and yearly values. However, it is important to note that there is an energy closure problem for the data from the Ameriflux sites. The difficulty encountered at the Ameriflux sites is that net radiation does not equal latent heat flux and sensible heat flux combined. Comparisons of modeled and predicted values were performed. Table 2 depicts the information, operator, and time from which data were acquired from each of the stations. Figure 3, gives general results of the total amount of ET recorded from these stations.

Table 3: Evapotranspiration Flux Tower Data

Station ID	Flux Station	Operator	Vegetation	Units	Year
US-Mpj	Mountainair	Dr. Marcy Litvak	Open Shrub/ Pinion/ Juniper	mm/day	2008-2010
US-Seg	Sevilleta	Dr. Marcy Litvak	Desest Grassland	mm/day	2007-2010
US-Ses	Sevilleta	Dr. Marcy Litvak	Desert Shrubland	mm/day	2007-2010
US-Vcm	Valles Caldera	Dr. Marcy Litvak	Evergreen/ Mixed Conifer Forest	mm/day	2007-2010
US-Vcp	Valles Caldera	Dr. Marcy Litvak	Evergreen/Ponderosa Pine Forest	mm/day	2007-2008
US-Wjs	Williard	Dr. Marcy Litvak	Juniper Savanna Shrubland	mm/day	2008
Bosque	Sevilleta	Dr. Salim Bawazir	Bosque Salt Cedar	mm/day	2005
Jornada	Jornada	Dr. Enrique Vivoni	Desert Shrubland	mm/day	Nov 2010 – Aug 2011

Note: Measurements are continuing at some of these sites but the data are not publically available.

Map 3: Flux Towers in New Mexico



This map depicts the flux stations with Eddy Covariance Systems across New Mexico. These data were used to compare measured and modeled Evapotranspiration values from ALEXI, SSEB, MOD16, and METRIC.

Imagery Source: ESRI, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/ Airbus DS, USDA, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

Map Created by: Francisco Ochoa
Date: 6/2/2016
Coordinate System: UTM Zone 13N
Datum: NAD 1983

Flux Stations

Eddy Coviarance System

0 50 100 Km

N W E S

Spatial Distribution of Flux Towers

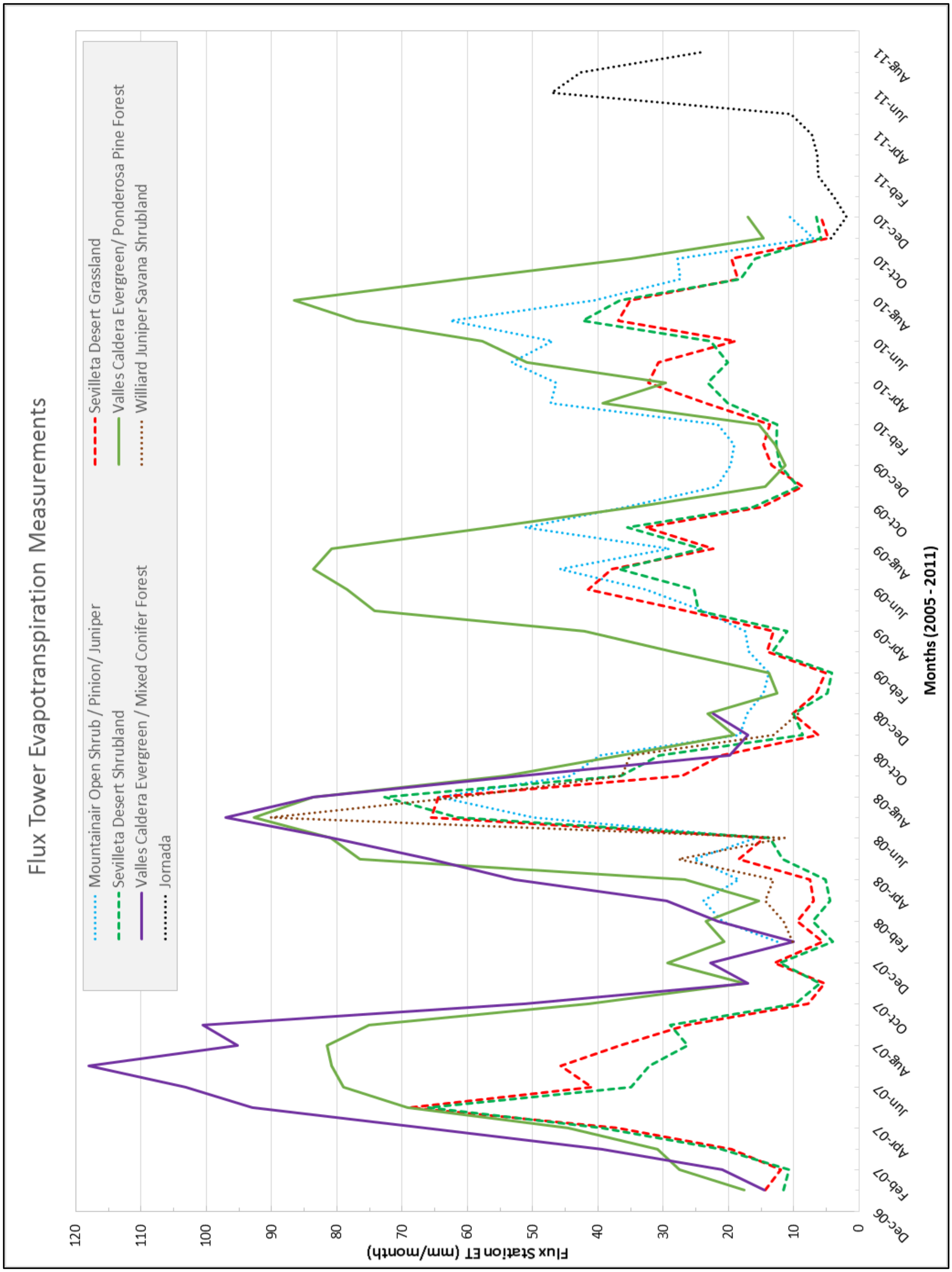


Figure 3: Total Monthly Recorded ET at Flux Stations (not including Bosque Salt Cedar)

3.1 Results from MOD16

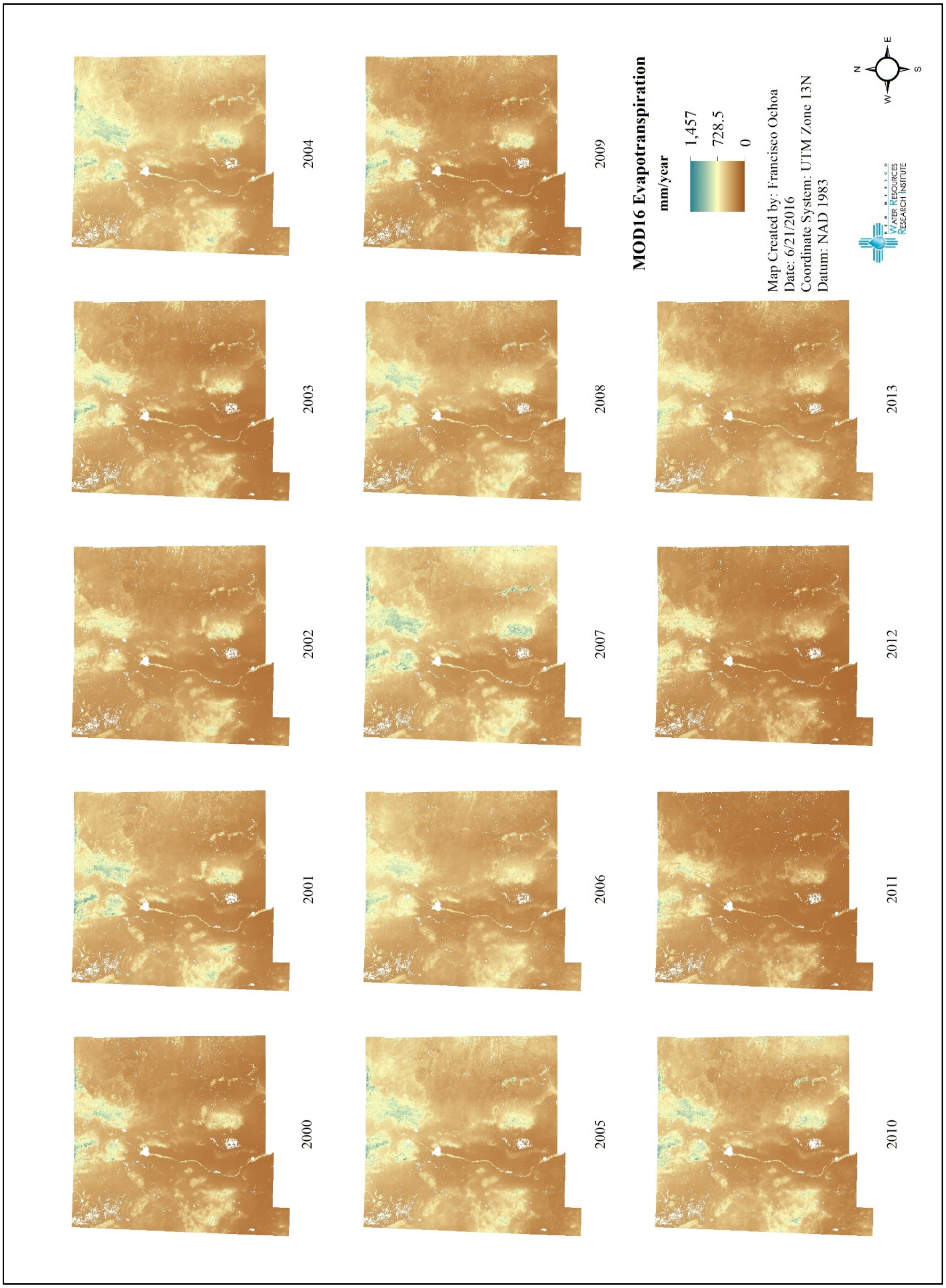
Yearly MOD16 data analyzed from 2005 to 2010 indicated a very low correlation between MOD16 and ET flux stations scattered across New Mexico. The r^2 value of this yearly regression is 0.23, the lowest correlation out of the models analyzed. Results indicate that this model is under-predicting ET, something which was observed during the initial quantification of ET values statewide, see figure 1. In order to analyze where the model works with more precision in New Mexico, flux stations and pixels were analyzed individually for their respective time periods.

Monthly regressions returned interesting results, with the flux station labeled Valles Caldera Evergreen / Mixed Conifer Forest having the greatest r^2 value of 0.71. In the Valles Caldera Evergreen / Ponderosa Pine Forest flux station, the r^2 value was 0.69. The flux station labeled Bosque Salt Cedar, located in a riparian area recorded high levels of actual ET during the year 2005. The monthly comparison at Bosque Salt Cedar demonstrated a correlation of 0.04, indicating that the model does not perform effectively in riparian areas since Bosque Salt Cedar is situated in one. By removing the yearly values of Bosque Salt Cedar in the yearly regression, yearly r^2 values increased to 0.91 from 0.23, indicating a strong correlation between the other sites and MOD16. This can also be an indication that the model does not perform well during a wet year.

MOD16 also performed very poorly in the Sevilleta, as both stations, Sevilleta Desert Shrubland and Sevilleta Desert Grassland showed a non-existent correlation. Flux station labeled Mountainair had a r^2 value of 0.11. Using this product would require further calibration and specifications for riparian areas and other areas where the model might not be as accurate. When analyzing the time series, Map 4, MOD16 fails to pick up spatial variation across the topographical landscape.

There also seems to be some sort of homogenous ET patterns in the southern parts of New Mexico and the model does not appear to indicate agricultural areas. Furthermore, when looking for an ET / P ratio in closed basins, it is assumed that ET and precipitation are similar in value; based on the results from figure 3, MOD16 will always make precipitation a larger component of this ratio. Therefore, due to these uncertainties, MOD16 does not represent accurate ET estimates across New Mexico.

Map 4: MOD16 Yearly Time Series 2000-2013



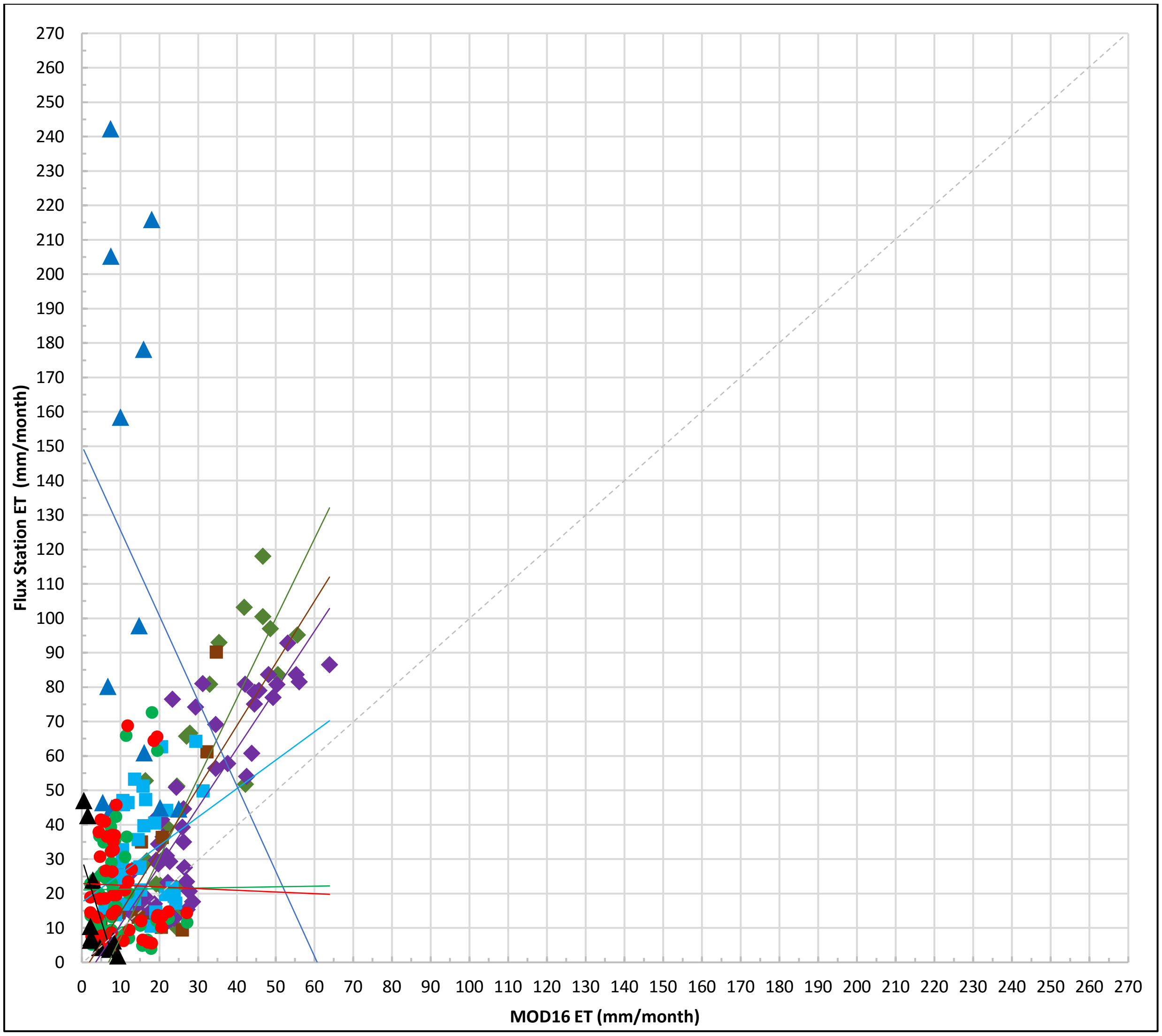


Figure 4: MOD16 Monthly Validation with Flux Towers

Table 4: MOD16 Monthly Regression Results

Key	ID	Flux Station	Vegetation	Year	RMSE	R^2
♦	Vcm	Valles Caldera	Evergreen/ Mixed Conifer Forest	2007-2010	22.77	0.71
♦	Vcp	Valles Caldera	Evergreen/ Ponderosa Pine Forest	2007-2008	34.35	0.69
■	Wjs	Williard	Juniper Savanna Shrubland	2008	21.25	0.51
▲	Jornada	Jornada	Desert Shrubland	11/10–8/11	21.18	0.43
■	Mpj	Mountainair	Open Shrub/ Pinion/ Juniper	2008-2010	20.69	0.11
▲	Bosque	Bosque	Salt Cedar	2005	129.17	0.04
●	Seg	Sevilleta	Desert Grassland	2007-2010	21.09	0.00
●	Ses	Sevilleta	Desert Shrubland	2007-2010	20.35	0.00

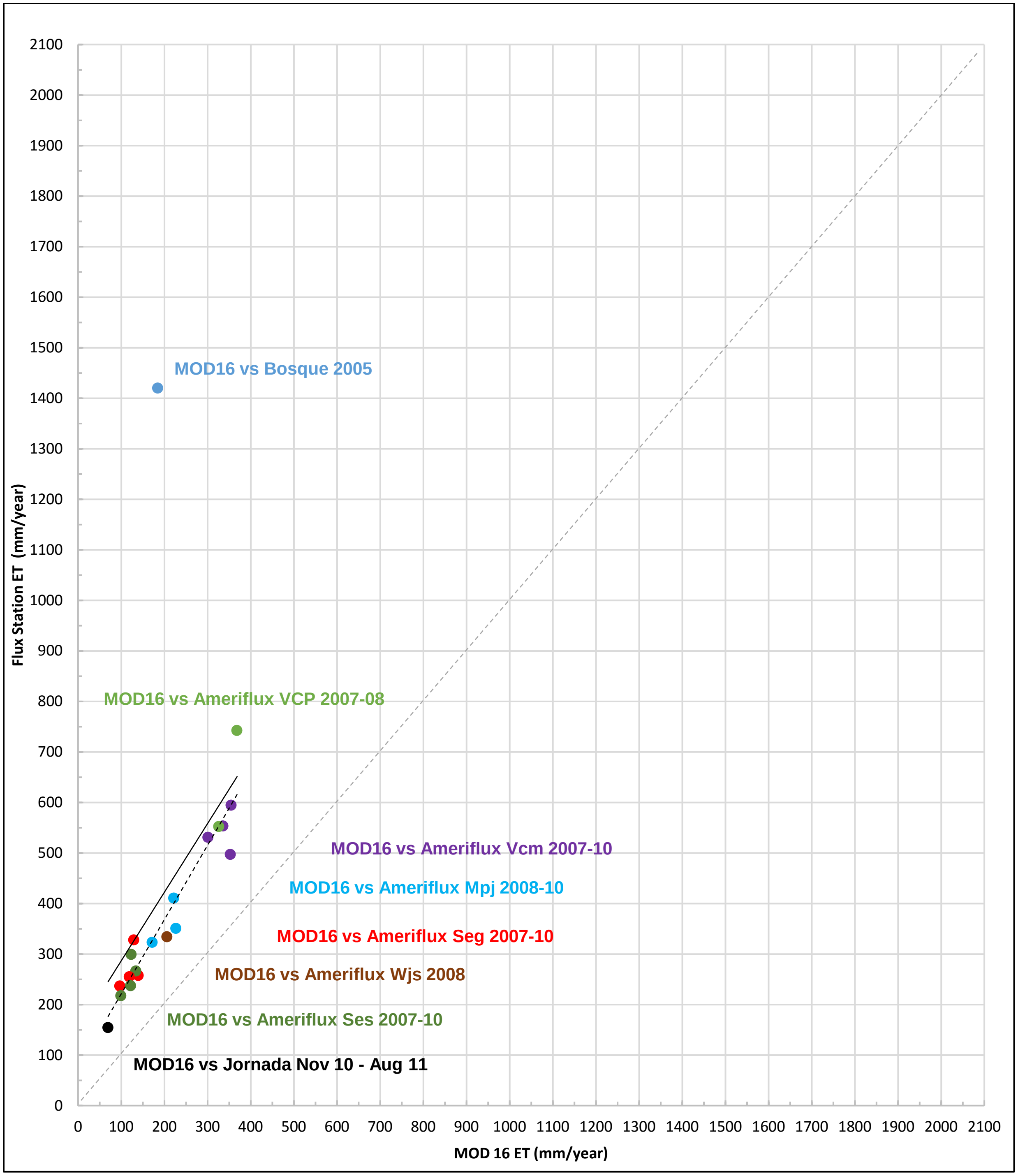


Figure 5: MOD16 Yearly Validation with Flux Towers

Table 5: MOD16 Yearly Regression Results

Key	Series	Year	RMSE	R^2
—	All ET Flux Stations	2005-2010	328.63	0.23
---	All ET Flux Stations (no Bosque Salt Cedar)	2007-2010	182.50	0.91

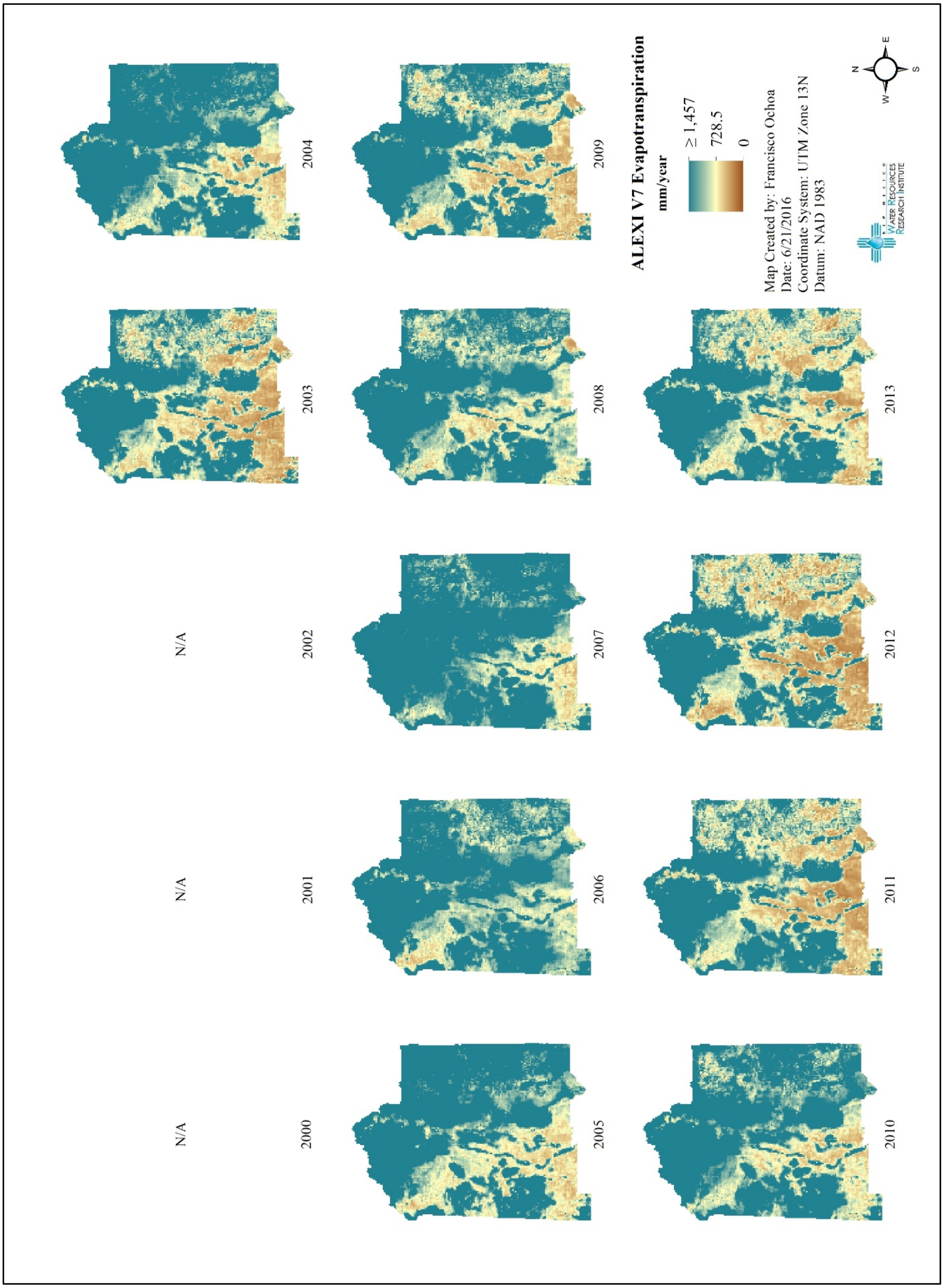
3.2 Results from ALEXI V7

ALEXI V7 is the latest version of the original ALEXI model, however, V7 is still considered a research version and not completely quality controlled. Yearly ALEXI V7 data analyzed from 2005 to 2010 indicated a very low correlation between modeled and ET flux stations values. ALEXI V7 yearly r^2 values were 0.34, with ET being overpredicted generally. In order to see where the model performs with more accuracy, data were regressed in a monthly time series and results indicated that the model performs poorly in mountainous and non-mountainous areas. Although the spatial variability of the terrain was captured, the model seemed to over and under predict ET in certain areas.

The highest r^2 value was recorded in the Valles Caldera Evergreen / Ponderosa Pine Forest flux station, with a r^2 value of 0.56, showing that ALEXI V7 works poorly in mountainous areas. In the Valles Caldera Evergreen / Mixed Conifer Forest flux station, the r^2 value was 0.52. Bosque Salt Cedar, the flux station situated in a riparian area, recorded high values of ET during 2005 and showed a r^2 value of 0.22, indicating a poor correlation in riparian areas or wet years. Although Bosque Salt Cedar and ALEXI showed a poor correlation, removing this flux tower's data from the yearly regression analysis increased the yearly r^2 value to 0.91, indicating a strong correlation between yearly modeled and observed values. However, this leads to the same problem that was encountered in MOD16, the model not performing effectively in certain areas or possibly during wet years.

The comparison between the Jornada Desert Shrubland flux station readings and ALEXI V7, from November 2010 to August 2011, showed a weak correlation with a r^2 value of 0.0016. Therefore, this model performs poorly in non-mountainous areas as this flux station is situated in the JER, where ET should be almost equal in value to the precipitation. Purely based on the regression analysis, figure 5, ALEXI V7 predicts ET with low accuracy in riparian and agricultural areas while it over predicts ET in mountainous regions.

Map 5: ALEXI V7 Yearly Time Series 2000-2013



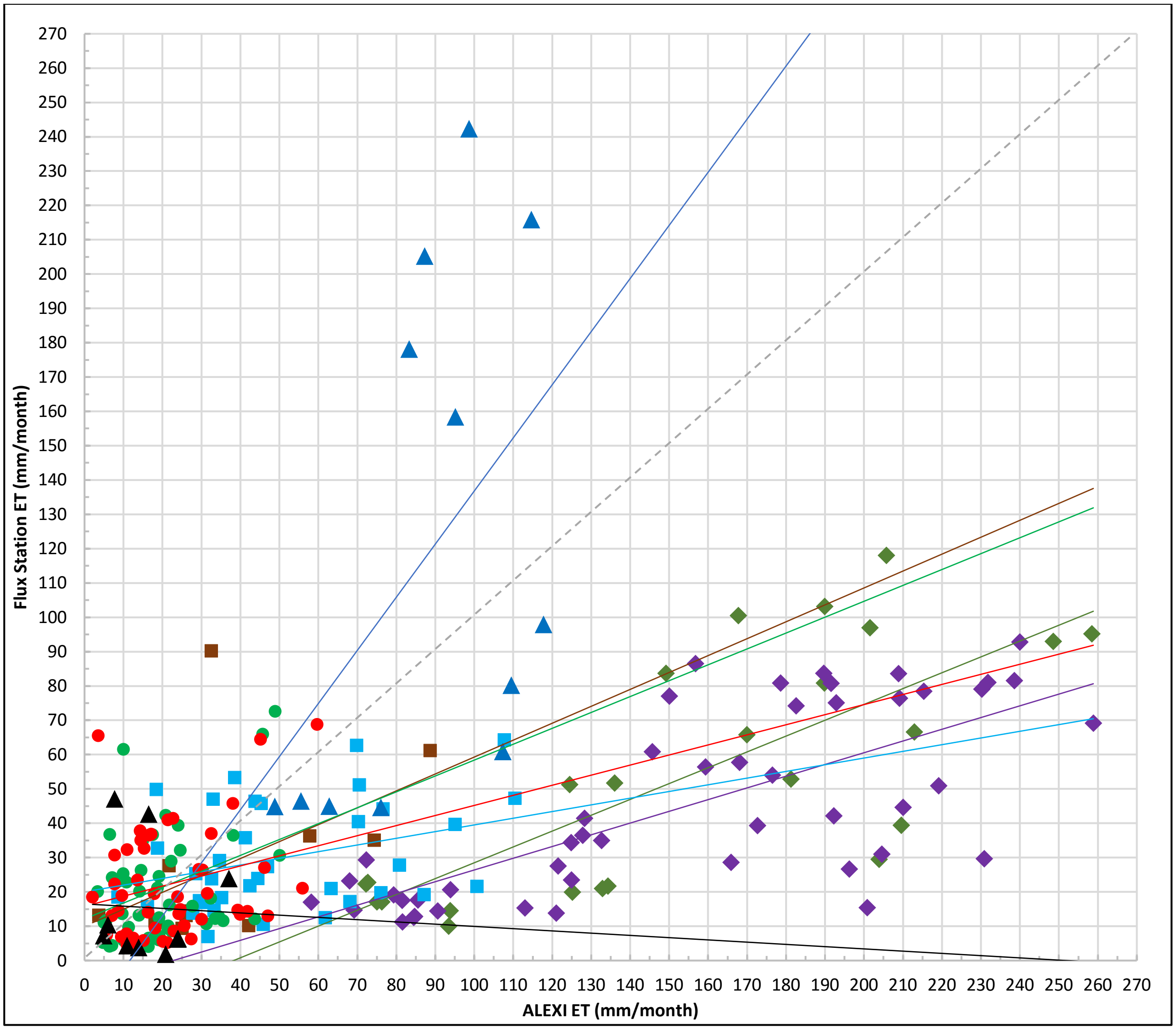


Figure 6: ALEXI V7 Monthly Validation with Flux Towers

Table 6: ALEXI V7 Monthly Regression Results

Key	ID	Flux Station	Vegetation	Year	RMSE	R^2
♦ (green)	Vcp	Valles Caldera	Evergreen/ Ponderosa Pine Forest	2007-2008	107.95	0.56
♦ (purple)	Vcm	Valles Caldera	Evergreen/ Mixed Conifer Forest	2007-2010	117.57	0.52
■ (brown)	Wjs	Williard	Juniper Savanna Shrubland	2008	25.58	0.25
▲ (blue)	Bosque	Bosque	Salt Cedar	2005	72.24	0.22
● (green)	Ses	Sevilleta	Desert Shrubland	2007-2010	16.35	0.12
■ (light blue)	Mpj	Mountainair	Open Shrub/ Pinion/ Juniper	2008-2010	33.75	0.12
● (red)	Seg	Sevilleta	Desert Grassland	2007-2010	18.32	0.06
▲ (black)	Jornada	Jornada	Desert Shrubland	11/10–8/11	18.85	0.00

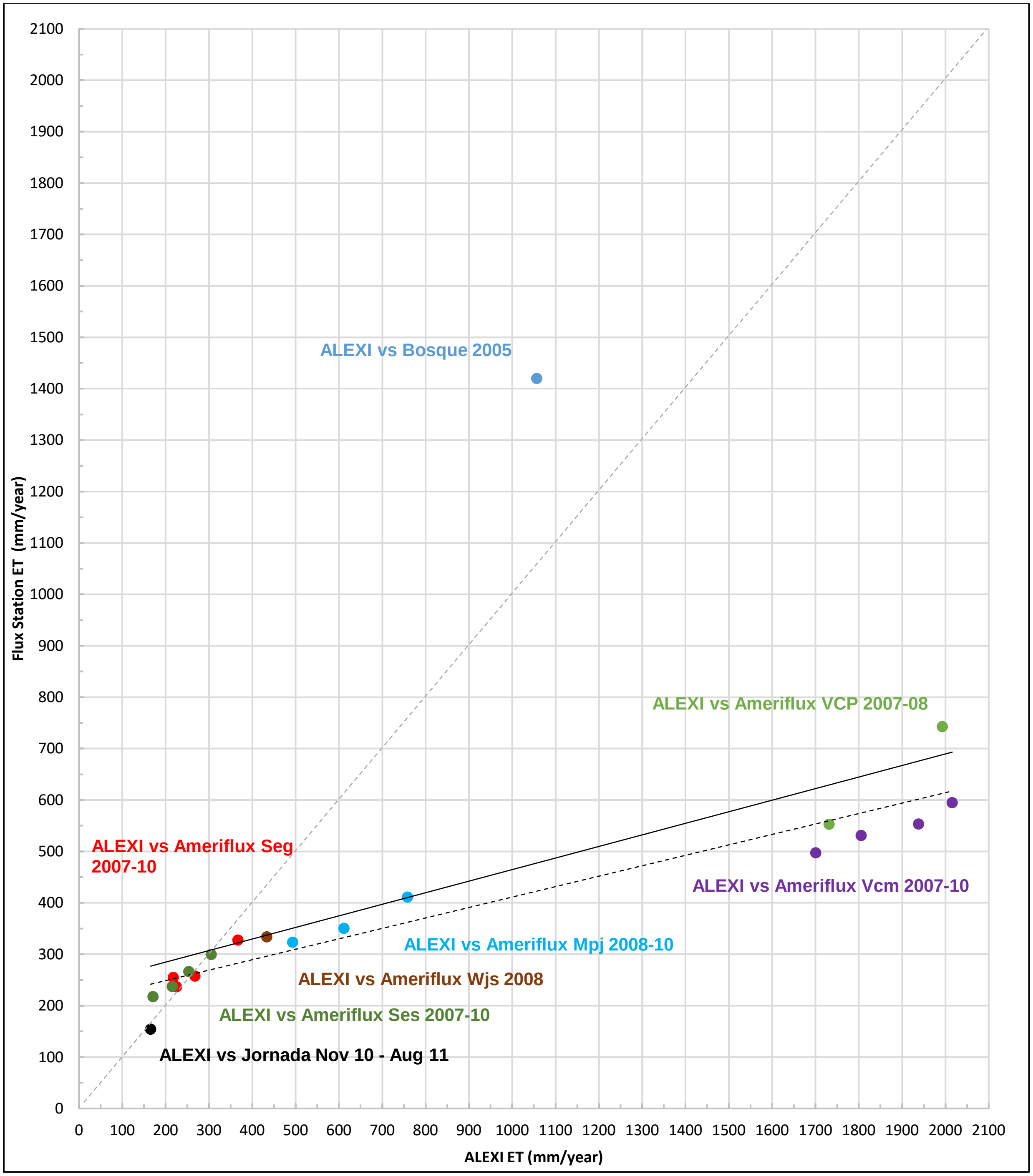


Figure 7: ALEXI V7 Yearly Validation with Flux Towers

Table 7: ALEXI V7 Yearly Regression Results

Key	Series	Year	RMSE	R^2
—	All ET Flux Stations	2005 - 2010	718.86	0.34
---	All ET Flux Stations (no Bosque Salt Cedar)	2007 - 2010	732.80	0.91

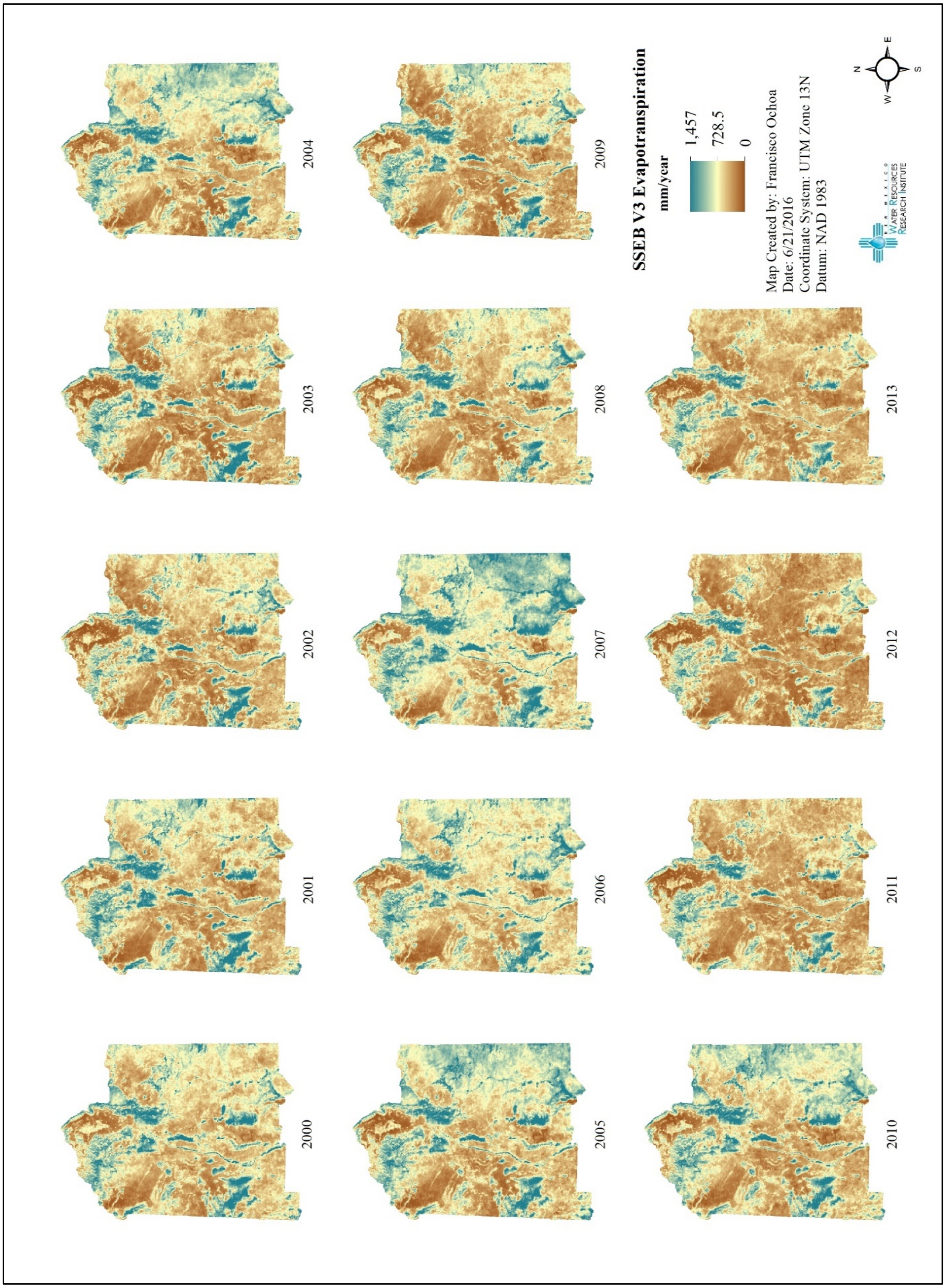
3.3 Results from SSEBop V3

SSEBop V3, the latest version of the SSEBop model, was analyzed on a yearly and monthly time scale from 2005 to 2011 and results indicated a low correlation between modeled yearly SSEBop V3 values and yearly ET flux stations recordings, with a r^2 value of approximately 0.58. This was the highest r^2 value out of the all the models analyzed in this study. This low result of r^2 is a probable error originating from the input data of the model, the coarse resolution of the air temperature grids. The model demonstrates favorably the spatial variability of the terrain and agricultural areas across New Mexico. Individual comparisons were implemented to explore areas where the model performs more effectively.

Bosque Salt Cedar, the flux station that recorded high levels of ET in 2005, partly because of its location in a riparian area, indicated that the model performs accurately in dense canopy areas or riparian areas. In a monthly comparison between observed and predicted values in 2005, the r^2 value was 0.89. This r^2 value was the highest in all the models analyzed at a monthly time scale. Removing Bosque Salt Cedar from the yearly regression analysis increased the yearly r^2 value to 0.77, indicating a strong correlation. In the mountainous areas, SSEBop performed efficiently, r^2 values were 0.88 and 0.73 in the Valles Caldera Evergreen / Ponderosa Pine flux station and Valles Caldera Evergreen / Mixed Conifer Forest flux station respectively. In the Willard Juniper Savanna Shrubland flux station the model and observed ET readings had a r^2 value of 0.83, indicating a strong correlation.

Comparing the Jornada Desert Shrubland flux station readings, from November 2010 to August 2011, SSEBop V3 and observed values showed a strong correlation with a r^2 value of 0.78. With this r^2 value from SSEBop V3 at the JER, an ET / P ratio can be developed for the Jornada Draw watershed. Since the Jornada Draw watershed is situated in a desert shrubland environment and a closed river basin, the precipitation should be almost equal to the evapotranspiration [Schmugge et al. 2013]. Using this information we can determine in this basin how much SSEBop V3 is over or under predicting ET. Therefore, out of the three models analyzed, SSEBop V3 is the model that most accurately displays ET across New Mexico.

Map 6: SSEBop V3 Yearly Time Series 2000-2013



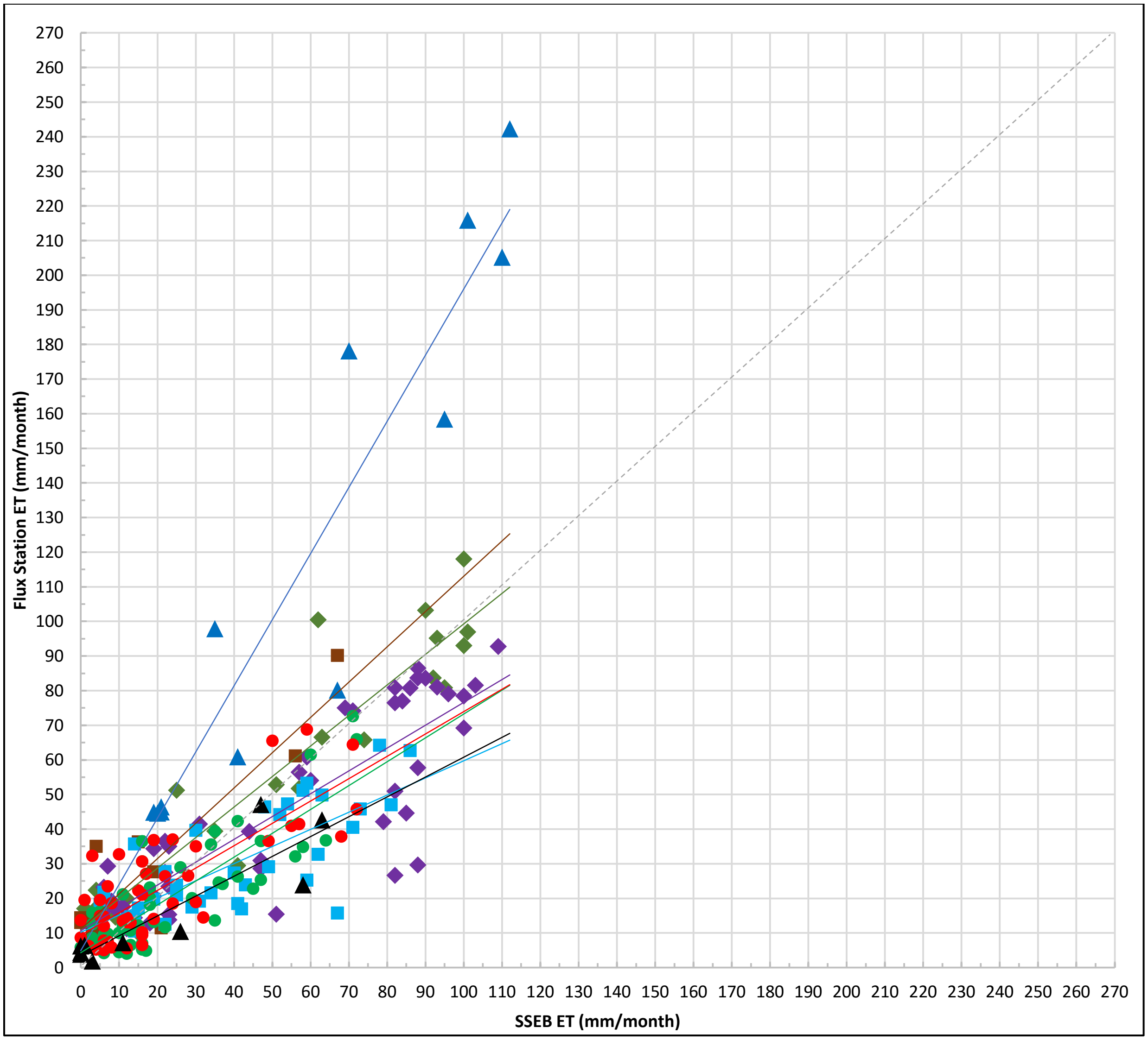


Figure 8: SSEBop V3 Monthly Validation with Flux Towers

Table 8: SSEBop V3 Monthly Regression Results

Key	ID	Flux Station	Vegetation	Year	RMSE	R^2
▲	Bosque	Bosque	Salt Cedar	2005	71.88	0.89
◆	Vcp	Valles Caldera	Evergreen/ Ponderosa Pine Forest	2007-2008	13.63	0.88
■	Wjs	Williard	Juniper Savanna Shrubland	2008	15.16	0.83
▲	Jornada	Jornada	Desert Shrubland	11/10-8/11	13.92	0.78
◆	Vcm	Valles Caldera	Evergreen/ Mixed Conifer Forest	2007-2010	19.46	0.73
●	Ses	Sevilleta	Desert Shrubland	2007-2010	11.11	0.70
●	Seg	Sevilleta	Desert Grassland	2007-2010	12.11	0.64
■	Mpj	Mountainair	Open Shrub/ Pinion/ Juniper	2008-2010	18.41	0.58

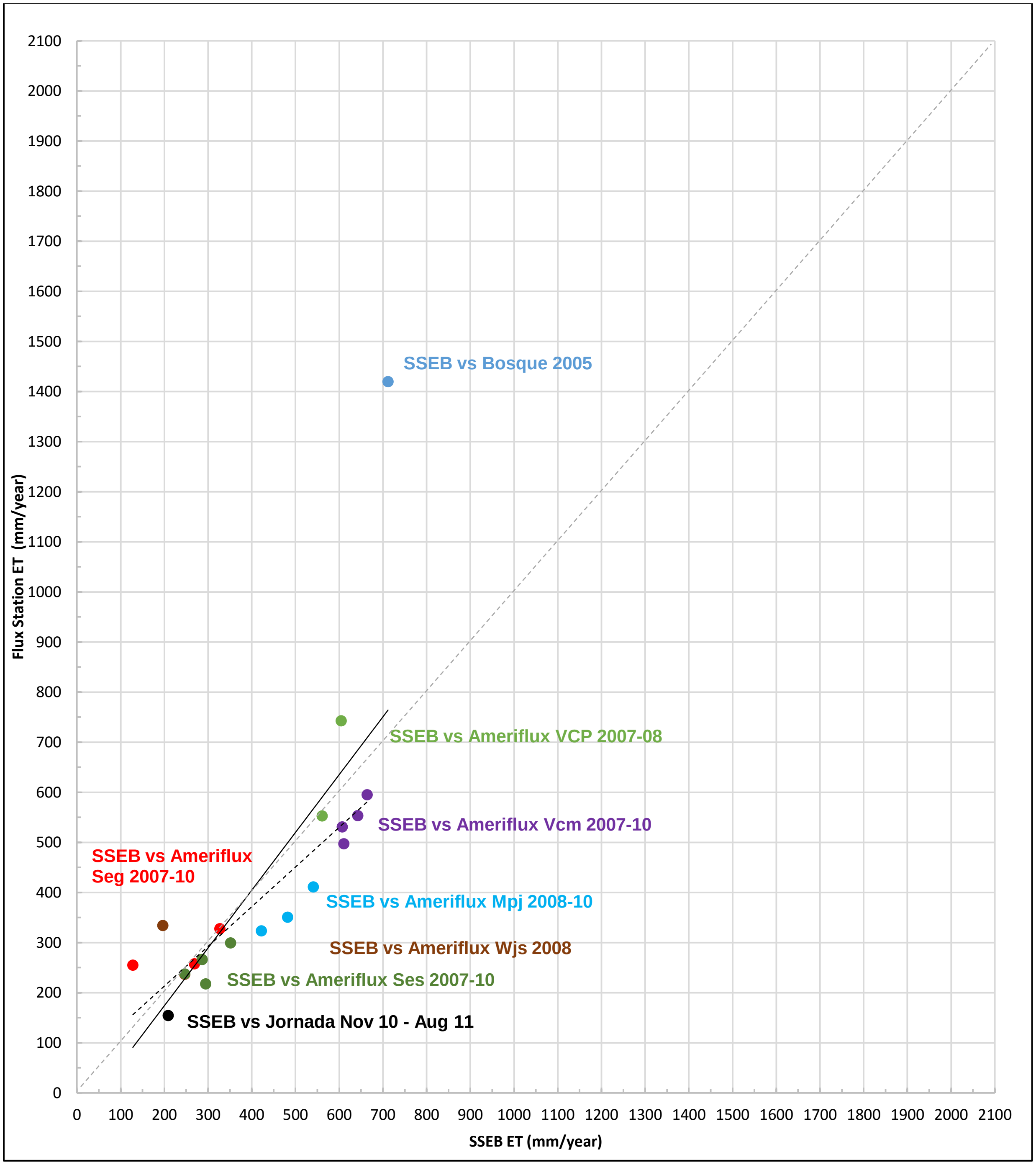


Figure 9: SSEBop V3 Yearly Validation with Flux Towers

Table 9: SSEBop V3 Yearly Regression Results

Key	Series	Year	RMSE	R^2
—	SSEBop vs ET Flux Stations	2005 - 2010	179.35	0.58
---	SSEBop vs ET Flux Stations (no Bosque Salt Cedar)	2007-2010	86.50	0.77

4. Evapotranspiration / Precipitation Ratio in SSEBop

As stated earlier, knowing that these values between modeled SSEBop ET and observed ET characterize the best linear correlation of all the models, it could be possible to explore a ratio between evapotranspiration and precipitation to see if there is any consistency in this ratio across time in New Mexico. Figure 10 shows the monthly statewide averages of ET and precipitation compared to one another. In figure 10, one can see that during dry years, ET exceeds the total precipitation, which can imply two things;

- Error due to over-prediction
- The water being released back into the atmosphere is coming from somewhere else

For example, when there is less precipitation, groundwater aquifer extraction rates might increase. Several studies have reported the ratio of evapotranspiration to precipitation ranges anywhere from 0.65 in global landscapes to 1.07, 0.83 in other ecological biomes, such as a rangeland environment [Bohn et al 2016] [Nagler et al 2007]. The yearly ratio of ET / P was calculated for the entire study area, however, the study area was partitioned into the following spatial units:

- New Mexico Water Planning Regions
- Watersheds (HUC8s)
- Counties

This was done to see where in the state the model would perform most effectively and explore the relationship of land use / land cover with ET. For example, one would expect that the most forested counties such as Catron or Rio Arriba will have a greater amount of ET due to increased vegetation. Before calculating the ratios, yearly averages of ET and precipitation were derived for each of the three spatial divisions. The process was done in ArcGIS using the following tools and procedures:

1. Iterate yearly SSEBop ET and PRISM (precipitation) grids
2. *Calculate Zonal Statistics as Table* on each of the grids for each County, HUC8, and NMWPR
3. Extract the values to an excel table to develop an ET / P ratio

The results from this process were not what was expected. There was hardly any consistency between the ratios from 2000-2013, r^2 values were calculated to see if this ratio was consistent across time. Jornada Draw, the watershed where JER is situated and where ET should be almost equal to precipitation reported a yearly average ratio of 0.86 from 2000-2013 and a r^2 value of 0.05, making the ratios not consistent over time [Gutschick & Snyder 2006]. The highest four correlations between ratios from 2000-2013 can be found in Table 10.

Table 10: ET / P Ratios Correlations

Name	**Type**	**Average ET/P Ratio (2000-2013)**	**R^2**
Los Alamos	County	0.97	0.69
Blanco Canyon	HUC8	0.89	0.23
North Plains	HUC8	0.77	0.22
Jemez	HUC8	0.98	0.21

Based on the observations, no suitable ratio of ET to P can be established using this version of SSEBop. The high r^2 value in Los Alamos County is due to the small number of total pixels that compromise the county, annulling spatial variability and making it very homogenous. Although results from the literature indicate that the values of ET / P might be consistent for a small period of time, using yearly ratios did not provide any useful findings.

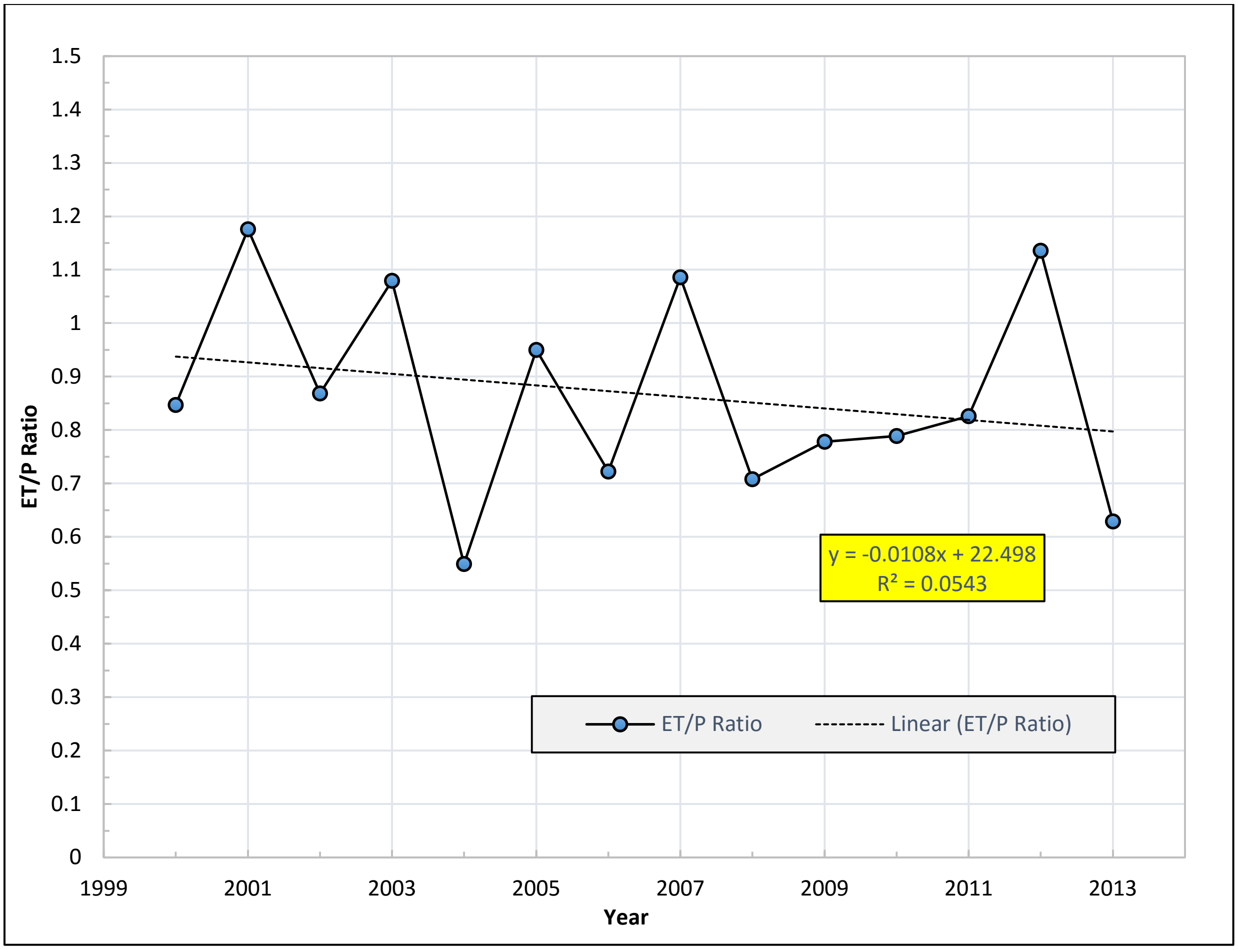


Figure 10: ET / P Ratios in the Jornada Draw Watershed

Table 11: Yearly Ratios of ET / P at the Jornada Draw Watershed

Jornada Draw ET / P Ratios					
Year	Ratio	Year	Ratio	Year	Ratio
2000	1.17	2005	0.94	2010	0.78
2001	1.17	2006	0.72	2011	0.82
2002	0.86	2007	1.08	2012	1.13
2003	1.07	2008	0.70	2013	0.62
2004	0.54	2009	0.77	2014	n/a

Note: This table represents the ratios of ET/ P ratios in the Jornada Draw Watershed. The average ET/P ratio from the years analyzed is 0.86.

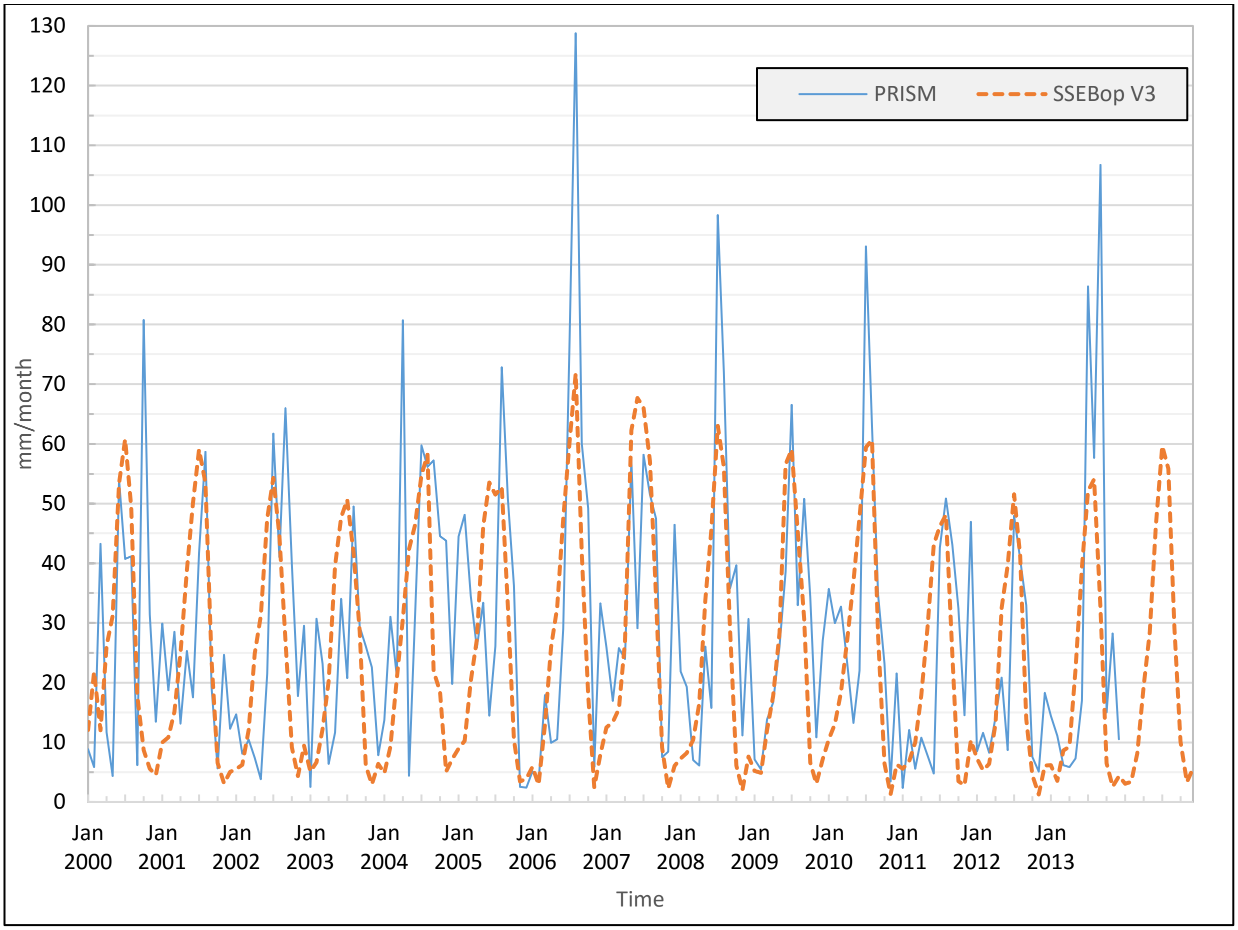


Figure 11: New Mexico SSEBop V3 ET & Precipitation Averages from 2000-2013

5. Justification for using the SSEBop in New Mexico

In conclusion, each model analyzed in this study performs differently and with varying degrees of accuracy. MOD16 showed a very low correlation between observed and predicted values. The newest version of ALEXI, V7, performs poorly in non-mountainous areas, over predicts ET, and its overall yearly correlation was low compared to observed values. On the other hand, SSEBop has the best linear fit with observed yearly and monthly values, therefore this model represents ET more accurately across the study area. Dr. Senay, the creator of the model, has mentioned that he is interested in improving the model statewide and this can be implemented in several ways. For example, since the model can be prepared with Landsat 8 Satellite Imagery, this will, in turn, create a finer resolution in the ET product that will have more accurate ET estimates.

5.1 Accounting for the Bias and Error in SSEBop

Like any model, SSEBop includes a degree of bias. A key component of this model is that it uses a topographic correction based on an atmospheric lapse rate for land surface temperature in order to reduce errors [Senay et al 2013]. Even with this topographic correction, most of the biases and overestimations in this model are originating from the air temperature grids used as input variables, the use of a constant temperature difference (Dt) function across large geographic space, and the use of the K parameter that scales up or down reference ET (ETo). Several implementations can be applied to reduce these biases.

The air temperature grids that this model uses, DAYMET, are produced from Oakridge Laboratories with a large spatial resolution of approximately 4 km by 4 km. This large spatial resolution is annulling the spatial variability of temperature due to surface topographic features in New Mexico. In the basin and range country, most of the temperature recording stations are located predominately in the basins and a small amount up in the mountains. These recorded temperature observations are being interpolated over areas where conditions are not similar to the temperature stations. For instance, if a temperature recording station is located at the base of Organ Peaks National Monument the temperature will not be the same in the mountain peaks since higher altitude areas tend to have lower atmospheric temperatures. This interpolation error simply causes mountain ranges with low vegetation to have similar values of ET compared to a mountain range with areas of high vegetation.

Another problem that affects SSEBop is the input data it uses for Reference ET. This reference ET comes from The University of Idaho Gridded Surface Meteorological Dataset and the same problem is encountered here as with the air temperature grids, a large spatial resolution. The value (K) which corresponds to the crop coefficient serves to upscale or downscale reference ET. Senay had stated that a good value for k is 1.2 for the entire Continental United States [Senay et al 2013]. However for a regional approach, a possible and more accurate k value might be developed for New Mexico.

5.2 Recommendations for Improving SSEBop & ET in New Mexico

Further research should be conducted to obtain a gridded product of air temperature and reference ET with fine spatial resolution. This would require validation to ensure high accuracy across New Mexico. Validation could be done using flux towers, scintillometers, and weather temperature stations. Using these field measurement tools requires installation, calibration, maintenance, and not to mention the associated costs that come with them. The placement of these towers and weather stations should be done with special care and planning, as the locations must consider different environmental biomes. Therefore, by putting these stations in different biomes, such as mountainous areas, woody encroachment areas, and agricultural fields, the data recorded will help capture the different spatial variability of the terrain, thus reducing the model bias and improving ET estimates.

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