Improving Evapotranspiration Estimation Using Remote Sensing Technology

By

Zohrab A. Samani, Professor

A. Salim Bawazir, Associate Professor

Civil Engineering Department

New Mexico State University

TECHNICAL COMPLETION REPORT

ACCOUNT NUMBER (Index #): **125548**

June 2015

New Mexico Water Resources Research Institute

in cooperation with the

Civil Engineering Department

New Mexico State University

The research on which this report is based was financed by the State of New Mexico through the New Mexico Water Resources Research Institute.

DISCLAIMER

The purpose of the Water Resources Research Institute (WRRI) technical reports is to provide a timely outlet for research results obtained on projects supported in whole or in part by the institute. Through these reports the WRRI promotes the free exchange of information and ideas and hopes to stimulate thoughtful discussions and actions that may lead to resolution of water problems. The WRRI, through peer review of draft reports, attempts to substantiate the accuracy of information contained within its reports, but the views expressed are those of the authors and do not necessarily reflect those of the WRRI or its reviewers. Contents of this publication do not necessarily reflect the views and policies of the Department of the Interior, nor does the mention of trade names or commercial products constitute their endorsement by the United States government.

ACKNOWLEDGMENT

We appreciate the support and collaboration of Steve Walker in the analysis related to SSEB and ALEXI models. We also appreciate the contribution of graduate student Leba Tiep and the support of NMSU Civil Engineering Department and the New Mexico Water Resources Research Institute (WRRI) staff.

ABSTRACT

Management of water resources and its efficient use require modeling and quantifying the temporal and spatial variability of evapotranspiration (ET) for a large area. There are many models that can be used to estimate ET of a large area but they vary in complexity, accuracy, and in some cases require specific expertise and high operational cost. Three remote sensing ET estimation models (REEM, SSEB and ALEXI) were evaluated and compared to ground-measured ET using energy budget method by Flux Towers in the Lower Rio Grande Basin (LRG) and the Middle Rio Grande (MRG) agricultural areas in New Mexico. The Flux Towers were located in the mature pecan orchard and alfalfa field in the Mesilla Valley of the LRG and in alfalfa field in the MRG. The ALEXI model ET estimates were consistently very low compared to REEM and SSEB models. The SSEB model ET estimates compared to REEM and Flux Tower ground measurements varied from 7% to 65%. The SSEB model comparison to REEM and Flux Tower where the fetch distance was within the SSEB resolution (i.e. 1 km pixel resolution) was reasonable during low ET rates. SSEB model requires further evaluation and can be improved to better estimate crops with high ET rates.

Keywords: Evapotranspiration, remote sensing, satellite, New Mexico, water resources, water management, water budget, energy budget, eddy covariance

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Understanding and modeling of water budget is the basis for the long-term management and sustainability of watersheds. The water budget of a typical basin consists of four components:

- Surface water budget
- Groundwater budget
- Precipitation
- Evapotranspiration (ET)

While the surface water budget can be determined through inflow-outflow monitoring, and the precipitation can be measured, the water budget for the interconnected groundwater and evapotranspiration is more complex. The critical step in understanding the water budget in a basin is the accurate estimate of ET. There are various methods of estimating basin wide ET. Among these methods, remote sensing technology is the most practical means of accounting for basin wide ET on a short time interval and regular basis. There are various remote sensing models such as METRIC (Allen et al 2007), SEBAL (Bastiaannsen, 1995), MODIS and ALEXI (Atmosphere Land Exchange Inverse) (Mecikalski et al. 2002). However, there are often significant variability between the ET estimates. One reason for the variability is the low resolution of Models such as MODIS. If low resolution models are going to be used for estimating ET for a large area (i.e. basin wide), they would need to be calibrated and validated using a high resolution model such as REEM (Samani et al, 2007). REEM uses high resolution Landsat-7 and Landsat-8 images with ground level ET flux measurements and climate data for calibration to estimate ET of a large area such as the Mesilla Valley in the Lower Rio Grande.

Efficient use and management of water resources require modeling and quantifying the temporal and spatial variability of ET for a large area. While models such as REEM can provide ET estimate with high resolution and relatively high accuracy, they require ground level ET flux and meteorological measurements for calibration as well as elaborate analysis. The process is time consuming and costly. Other models such as SEBAL (Bastiaannsen, 1995) and METRIC

(Allen et al., 2007) use arbitrary selection of ground level cold and hot pixel for calibration. The process in both SEBAL and METRIC is prone to large error due to lack of ground level measurements, and both models are time consuming and costly too, making them impractical for large scale modeling of ET. Currently there is no simple and accurate model for large scale modeling of ET. The SSEB model (Senay et al., 2007, Senay et al., 2011b, Senay et al., 2013; Singh et al., 2014;) offers a promising approach for such purpose, but the SSEB model is subject to large error when compared with measured and calibrated remote sensing modeled ET values. However, if the SSEB model can be modified and validated, it can become a potentially practical and low cost model for large scale estimation of ET and can be used in the water budget for management purposes.

OBJECTIVE

The main objective of this proposal was to evaluate the suitability of SSEB in estimating regional evapotranspiration. Evapotranspiration estimates from remote sensing models REEM, SSEB and ground-measured ET are compared and the results presented. In addition, a comparison was made between ALEXI, REEM, SSEB, and ground measurements. The SSEB ET data was generated from MODIS images with a 1 km thermal band resolution while ALEXI was generated from GOES images with a 5 km resolution. ET estimates of the agricultural areas of the Lower and Middle Rio Grande Valleys was estimated using the REEM model based on LandSat5, LandSat7, and LandSat8 with thermal band resolution ranging from 90-120 m. Ground level ET measurements were made by ET flux tower in alfalfa and pecan using eddy covariance systems.

METHODOLOGY

The ET generated by REEM (Regional ET Estimation Model) was compared to other models such as SSEB (Simplified Surface Energy Balance; Senay et al., 2007; Singh 2014), METRIC (Mapping Evapotranspiration with Internalized Calibration; Allen et al., 2007a) and ALEXI (Atmosphere-Land Exchange Inverse; Mecikalski et al. 2002; Norman et al. 1995 Norman *et al.*, 2003;) as a check and verification of estimated ET.

REEM

Regional ET estimation model uses Landsat-5, 7 and 8 spectral images (hhttp://gloves.usgs.gov/) combined with ground level climate and ET flux measurements to calculate daily ET and crop coefficient using surface energy balance method. The ground measured ET flux data is used to calibrate the REEM for the days when the satellite images are available. The calibrated model can then be used to forecast ET and crop coefficient for other days of the growing season. REEM is based on surface energy balance similar to that presented by Bastiaanssen et al. (1995) where the latent heat flux (LE) is determined as a residual of the surface energy equation:

$$LE = R_n - G - H \qquad (1)$$

where, LE is the latent heat flux, R_n is the net radiation flux determined using the algorithm developed by Samani et al. (2007), G is the soil heat flux and H is the sensible heat flux (all units are in MJ/m^2 per day). The LE is converted to equivalent depth of water or ET (mm) by dividing LE by latent heat of vaporization of water (λ) and density of water (ρ). The λ of water is about 2.45 MJ/kg at a temperature of 20 ^{o}C and does not differ significantly over the normal temperatures required for plant growth or during the growing season.

The details of ET estimation using REEM can be found in Samani et al. (2009). The REEM has been successfully used in estimating ET of agriculture crops (Samani et al., 2009) and in riparian vegetation (Bawazir et al., 2009). Landsat images coupled with ground level measurements of LE, H, Rn, G, and climate data are used in REEM model to generate maps of crop ET and crop coefficients.

SSEB

The Simplified Surface Energy Balance (SSEB) model was developed by Senay et al. (2007) and later revised to include both elevation and latitude effects on surface temperature (Senay et al., 2011b). The SSEB model approach has been recently parameterized for operational applications and is renamed SSEBop (Senay et al., 2013). It has been used for estimating actual ET assessment of the Colorado River Basing (Senay et al., 2014) and the outcome results are promising. In this report SSEBop will be referred to as SSEB.

The SSEB model uses simulated hot and cold pixel for computing daily evapotranspiration. In SSEB model the actual evapotranspiration (ET_a) is determined by multiplying the calculated evapotranspiration fraction (ET_f) by short grass reference evapotranspiration (ET_o) and adjusted using a scaling coefficient (k). The evapotranspiration fraction, ET_f, is calculated using an empirically determined cold pixel temperature at the theoretical cold pixel and the temperature gradient (dT) at the theoretical hot spot.

ALEXI

The Atmosphere-Land Exchange Inversion (ALEXI) surface energy balance model (Anderson et al.1997; Mecikalski et al. 1999; Anderson et al. 2007a) was developed as an extension to the two-source model (TSM) of Norman et al. (1995). The ALEXI model is a multi-sensor TIR (Thermal infrared) method for ET mapping. ALEXI couples a two-source (soil and canopy) land-surface model with atmospheric boundary layer to calculate daily ET fluxes at continental scales and 5−10 km thermal band resolution and insolation estimates from geostationary satellites.

Ground-based Measurement of ET

Evapotranspiration flux tower are used to measure in-situ crop ET. The measured ET flux can be used for calibration and validation of ET models. The location of flux towers, crop type and year of measurements are listed in Table 1.

Table 1. Evapotranspiration flux tower location and crop

Station	**Year**	**Crop**	**Latitude**	**Longitude**
LRG-Pecan	2008	Pecan	32º 10′ 36.08″ N	106º 44′ 22.39″W
	2010	Pecan	32º 10′ 36.08″ N	106º 44′ 22.39″W
LRG-Alfalfa	2008	Alfalfa	32º 04′ 20.1″ N	106º 40′ 09.90″W
MRG-Alfalfa	2011	Alfalfa	34° 58′ 04.34″ N	106° 41′ 57.85″ W
	2013	Alfalfa	34° 58′ 04.34″ N	106° 41′ 57.85″ W

In the Lower Rio Grande, remote sensing ET output from the models were compared to measured ET from flux tower in a dense and mature pecan orchard [World Geodetic System (WGS 84): 32º10′ 36.08″ N, 106º 44′ 22.39″W and altitude 1144 m a.m.s.l.] and in alfalfa field [World Geodetic System (WGS 84) 32º 04′ 20.1″ N, 106º 40′ 09.90″W and altitude 1164 m a.m.s.l.]; In the Middle Rio Grande, model ET outputs were compared to ET measured by flux tower in alfalfa field [34°58’04.34” N, 106°41’57.85” W, elevation 1499 m a.m.s.l.].

Flood Plain Shape Files

In order to compare watershed scale ET estimates from REEM and SSEB, the entire agriculture watershed of the LRG (Figure 1) and MRG (Figure 2) were defined as shape files. The average monthly ET of the shape files were calculated and compared. An example of LRG and MRG ET values are shown in Figures 1 and 2.

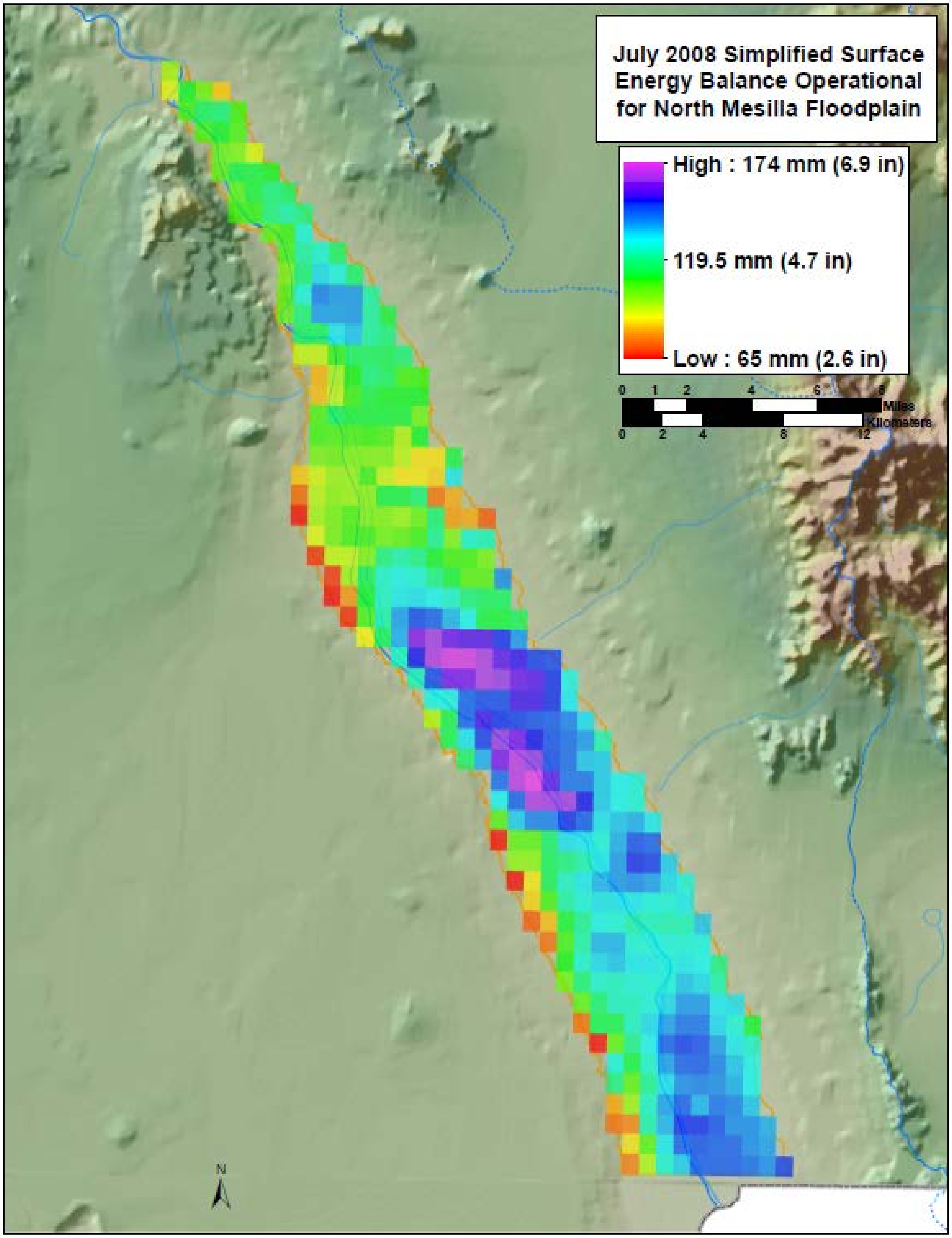

Figure 1. Lower Rio Grande (LRG) evapotranspiration map for the month of July, 2008

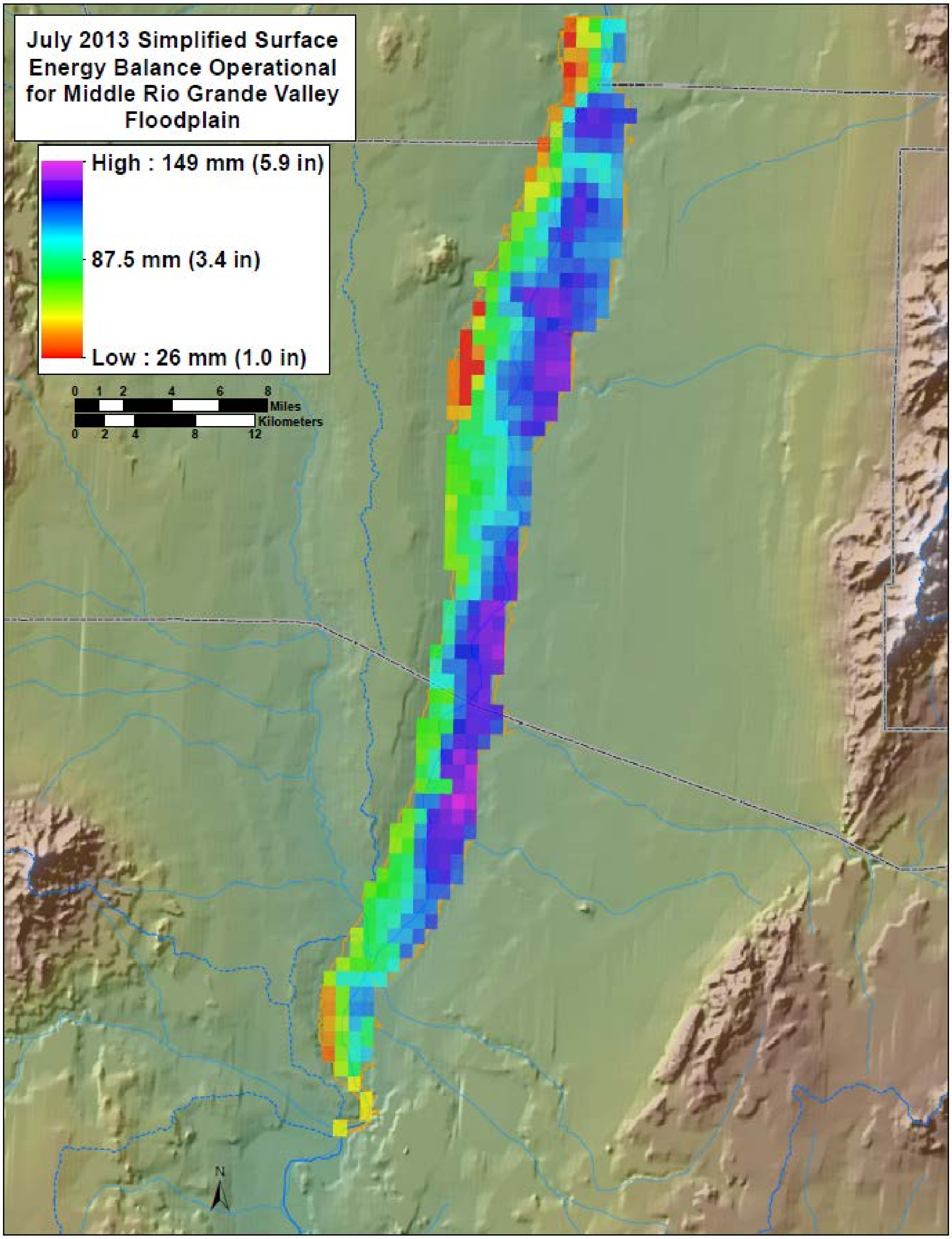

Figure 2. Middle Rio Grande (MRG) evapotranspiration map for the month of July, 2013

Pecan Orchard

The pecan orchard was located about 13 km south of Las Cruces, NM in the Mesilla Valley and adjacent to the Rio Grande. Pecan trees ranged in age from about 48 to 73 years and of the variety ‘Western Schley’. The trees were about 16 m tall on average with trunk diameters ranging from 38 to 50 cm and were spaced about 9 by 9 m. The orchard stretched about 2.4 km wide and 4.8 km long. The Rio Grande bordered the orchard on the east side. Agricultural lands surrounded the orchard and on the east side of the Rio Grande. The orchard was flood irrigated with water from the Rio Grande via irrigation canals and supplemental water from groundwater. The terrain of the orchard was laser leveled.

Energy budget (Equation 1) method utilizing eddy covariance technique was used to measure ET of mature pecan and dense pecan orchard. A 23-m triangulated tower was used to mount the sensors for measuring the components of the energy budget. The eddy covariance instruments were mounted on the tower at about 7 m above the canopy allowing a minimal fetch-to-instrument-height ratio of 1:340. The following are the sensors used in the measurement: Net radiation was measured using a Q7.1 net radiometer (Radiation and Energy Balance systems, Inc., Seattle, Washington); soil flux was measured using four soil heat flux (Radiation and Energy Balance systems, Inc., Seattle, Washington) buried at the surface with two under the canopy and two between the rows; sensible heat flux was measured using a pair of OPEC system (Amiro and Wuschke 1987; Blanford and Gay 1992; Bawazir 2000; Samani et al., 2009). A pair of OPEC system was used to ensure consistency in data collection. The OPEC system consisted of a gill propeller anemometer model 27106 (R.M. Young Company, Traverse City, Michigan) and a 76-µm diameter type E fine-wire thermocouple (Campbell Scientific Inc., Logan, Utah). The latent heat was calculated as a residual in the energy budget assuming the energy budget closed.

Alfalfa field

Similarly as pecan orchard, ET of alfalfa was measured using energy budget method (Equation 1) utilizing eddy covariance technique. One of the flux towers was located in an alfalfa field in the LRG and the other in the MRG. The sensors to measure components of the energy budget were installed on a 4.5 m triangulated tower in the LRG and 3 m triangulated tower with an extension rod at the top in the MRG. The flux tower in the LRG was located in a 29 ha field of alfalfa and in the MRG was located in the 20.23 ha of alfalfa. The fields were laser leveled and flood irrigated using the water from both the Rio Grande and the ground. Sensible heat (H) at both sites were measured using three-dimensional sonic anemometer (CSAT- 3D) by Campbell Scientific Inc. (CSI), Logan Utah and in addition OPEC system for comparison purposes and as a backup. Net radiation was measured using the NR-LITE net radiometer (CSI) and Q7.1 net radiometer (Radiation and Energy Balance Systems, Bellevue,WA), and soil heat (G) was measured using soil heat flux plates (REBS Inc.), soil moisture (CS 616 water content reflectometer by CSI) and averaging soil temperature probes (TCAV by CSI). The latent heat (or ET) was calculated as a residual in the energy budget.

RESULTS AND DISCUSSION

Evapotranspiration was compared for LRG and MRG using station flux tower measurements as well as the modelled ET for the entire watersheds using remote sensing REEM, SSEB, and ALEXI. The results are described and discussed in the following sections.

ET Comparison for the Lower Rio Grande (LRG)

LRG Flux Tower Stations

Monthly ET of REEM, SSEB, ALEXI and ground-measured ET (Flux Tower) of pecan orchard for year 2008 are presented in Table 2 and Figure 3. Flux Tower ET was consistently higher when compared to model ET estimates by REEM, SSEB and ALEXI. The ALEXI model results were consistently very low compared to the REEM, SSEB and Flux Tower. Annual ET was 1422.81 mm, 1248.20 mm, 988 mm, and 480.74 mm, respectively. One reason for underestimation of ET by SSEB and ALEXI could be due to the edge effect caused by large pixel size (1 km for SSEB and 5 km for ALEXI). Pecan orchard flux tower had a fetch size of

2.5 km which is sufficient to remove the edge effect of 1 km resolution but not enough for the 5 km resolution. The very low values of ALEXI could be due to the edge effects in this case. The results also show that the SSEB model is underestimating the ET values despite having a sufficient buffer (i.e. edge effect).

Table 2. Lower Rio Grande Basin (LRG) measured pecan evapotranspiration (ET) and model estimates using remote sensing for 2008

Year	Month	Evapotranspiration (mm)			
		Pecan Flux Tower	REEM	SSEB	ALEXI
2008	January	56.20	30.40	15.00	11.98
2008	February	60.43	51.40	15.00	17.80
2008	March	57.00	77.80	22.00	23.54
2008	April	101.70	107.50	72.00	30.36
2008	May	168.30	158.00	138.00	32.60
2008	June	224.10	199.90	178.00	52.72
2008	July	205.40	166.00	157.00	92.99
2008	August	191.10	172.00	144.00	96.11
2008	September	183.60	147.00	119.00	44.84
2008	October	130.28	93.00	70.00	44.84
2008	November	20.10	28.60	39.00	14.86
2008	December	24.60	16.60	19.00	18.10
	Total	**1422.81**	**1248.20**	**988.00**	**480.74**

Monthly ET of REEM, SSEB, ALEXI and ground-measured ET (Flux Tower) of alfalfa field for year 2008 are presented in Table 3 and Figure 4. This comparison shows a larger difference between the SSEB, ALEXI and the measured ET and REEM generated ET. This can be attributed to lack of sufficient fetch distance for SSEB (1 km resolution) and ALEXI (5 km resolution) to eliminate the edge effect.

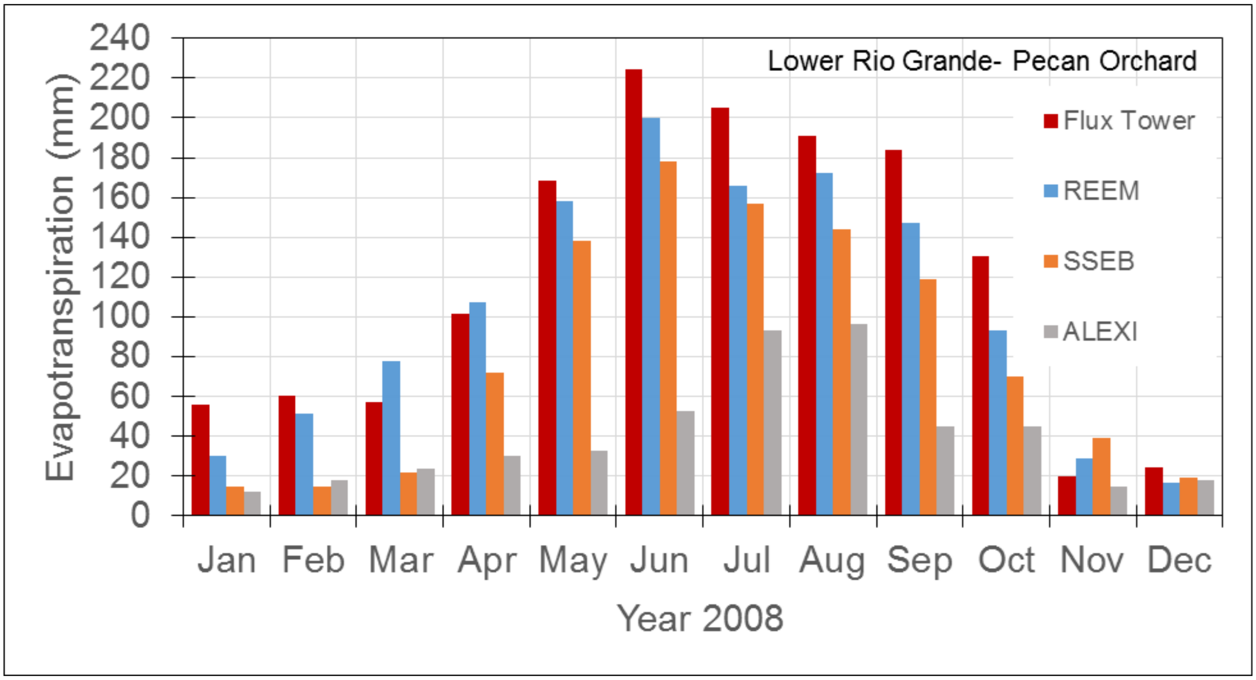

Figure 3. Monthly pecan evapotranspiration (ET) for year 2008 as estimated by REEM, SSEB and ALEXI, and ground-measured Flux Tower in the Lower Rio Grande (LRG)

Table 3. Lower Rio Grande Basin (LRG) measured alfalfa evapotranspiration (ET) and model estimates using remote sensing for 2008

Year	**Month**	**Evapotranspiration (mm)**			
		Flux Tower	**REEM**	**SSEB**	**ALEXI**
2008	January				
2008	February	36.9	37.00	11	23.4
2008	March	63.4	98.39	23	23.1
2008	April	161.5	133.79	68	32.8
2008	May	198.3	176.78	84	26.5
2008	June	197.1	207.26	117	54.8
2008	July	163.1	144.42	129	95.7
2008	August	176.00	140.42	138	96.6
2008	September	120.20	95.32	111	42.8
2008	October	130.6	76.50	53	42.8
2008	November	54.3	35.00	21	15.6
2008	December				
	Total	**1301.4**	**1144.88**	**755.00**	**454.1**

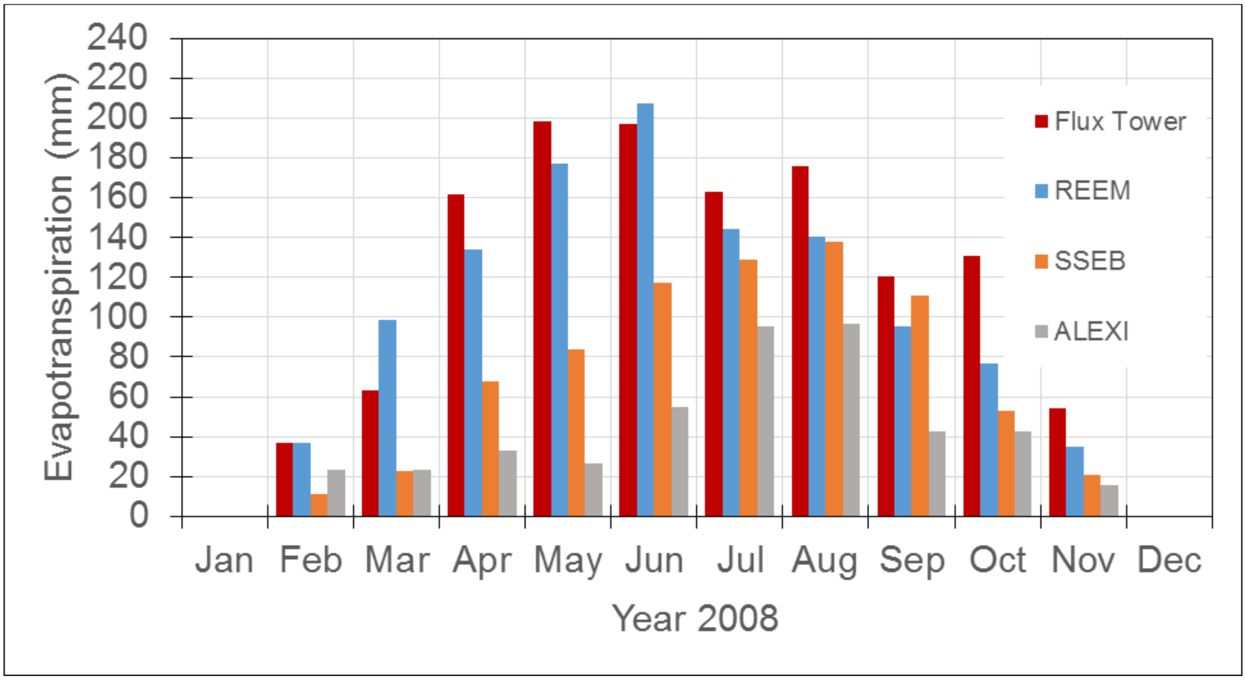

Figure 4. Monthly alfalfa evapotranspiration (ET) for year 2008 as estimated by REEM, SSEB and ALEXI, and ground-measured Flux Tower in the Lower Rio Grande (LRG)

LRG Watershed ET Comparison

A single shape file was used to define LRG watershed as shown in Figure 1. A comparison of monthly REEM and SSEB models for years 2008 and 2010 are shown in Figures 5 and 6 for the LRG agricultural area. Total annual ET estimated for 2008 by REEM was 704.5 mm and SSEB 751.28 mm; a difference of 46.78 mm. In this case SSEB estimate was higher than the REEM. Annual ET estimates of year 2010 was 1179.18 mm and 730.22 mm for REEM and SSEB, respectively; a difference of 448.96 mm. Monthly ET values are presented in Table 4.

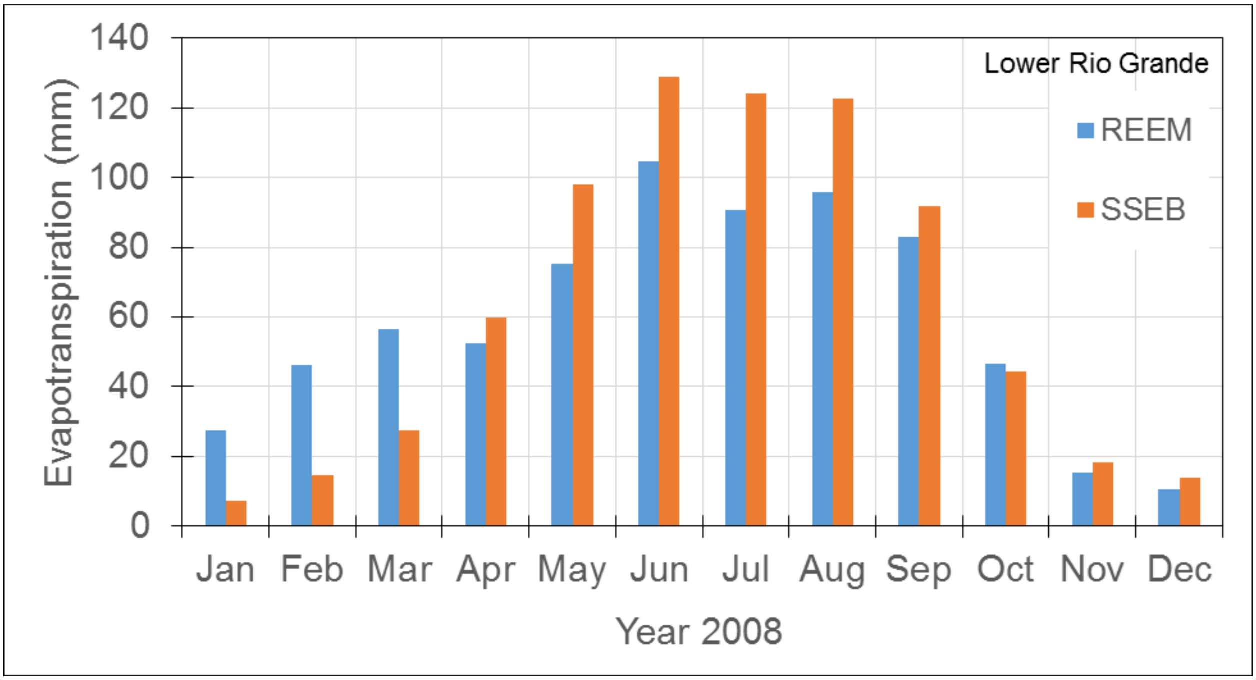

Figure 5. Monthly evapotranspiration (ET) estimated by REEM and SSEB models for year 2008

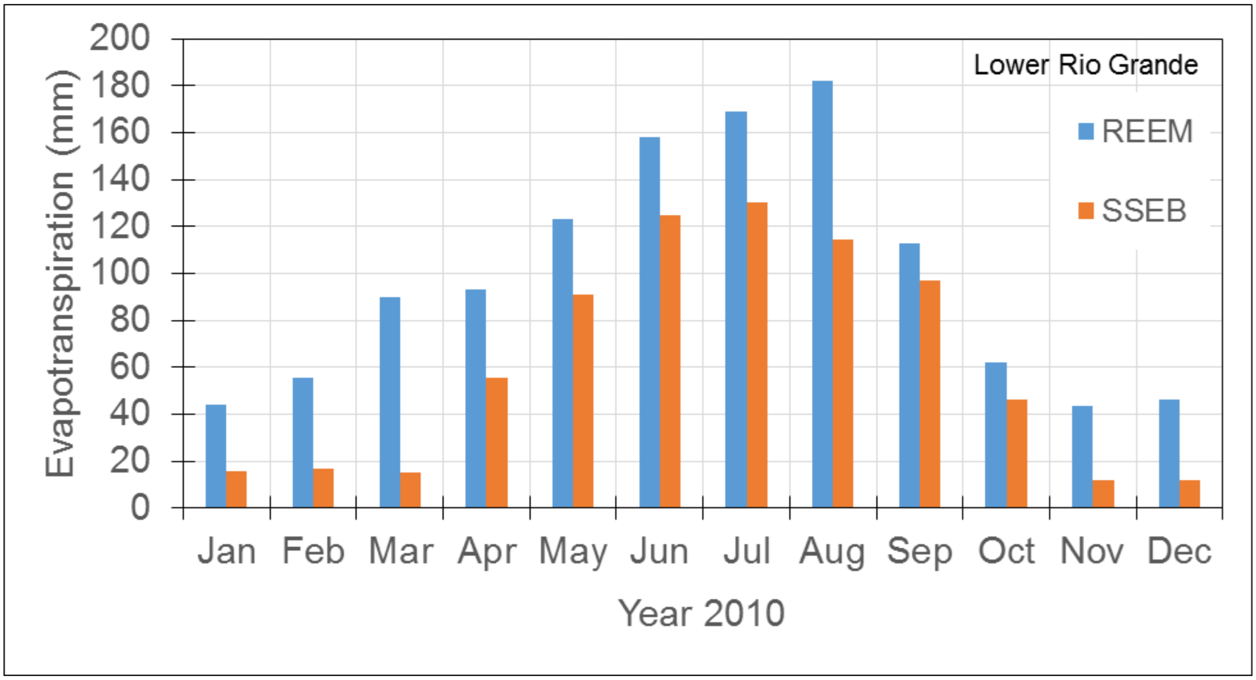

Figure 6. Monthly evapotranspiration (ET) estimated by REEM and SSEB models for year 2010

Table 4. Lower Rio Grande Basin (LRG) evapotranspiration estimates for years 2008 & 2010

Year	Month	Evapotranspiration (mm)	
		REEM	**SSEB**
2008	January	27.40	7.30
2008	February	46.37	14.70
2008	March	56.42	27.56
2008	April	52.57	59.65
2008	May	75.15	98.19
2008	June	104.62	128.76
2008	July	90.68	124.18
2008	August	95.78	122.58
2008	September	82.95	91.72
2008	October	46.58	44.51
2008	November	15.50	18.29
2008	December	10.48	13.84
	Total	**704.50**	**751.28**
2010	January	44.00	15.50
2010	February	55.34	16.53
2010	March	89.90	15.01
2010	April	93.14	55.32
2010	May	123.00	91.20
2010	June	158.20	125.06
2010	July	168.74	130.20
2010	August	182.20	114.20
2010	September	112.84	97.17
2010	October	62.10	46.00
2010	November	43.60	11.92
2010	December	46.12	12.11
	Total	**1179.18**	**730.22**

ET Comparison for the Middle Rio Grande (MRG)

MRG Flux Tower Station

Monthly ET of REEM, SSEB and ground-measured ET (Flux Tower) of alfalfa field during growing season from April through October for year 2013 are presented in Table 5 and shown in Figure 7. Flux Tower ET and REEM were consistently higher when compared to model ET estimates SSEB and ALEXI. Growing season ET for Flux Tower, REEM, SSEB and ALEXI was 930.64 mm, 951.50 mm, 325 mm and 199.74 mm (month of Sept. data was not available from ALEXI), respectively. The results from SSEB and ALEXI are considerably lower than the measured and the REEM simulated ET. Part of this discrepancy can be attributed to the pixel resolution resulting in edge effect in SSEB and ALEXI. However, most likely other factors may have contributed to this large difference. Additional investigation of the SSEB and ALEXI will be necessary to understand the contributing factors.

Table 5. Middle Rio Grande Basin (MRG) measured alfalfa evapotranspiration (ET) and model estimates for 2013

Year	**Month**	**Evapotranspiration (mm)**			
		Flux Tower	**REEM**	**SSEB**	**ALEXI**
2013	January				
2013	February				
2013	March	60.4	72.6	9	7.14
2013	April	183.8	189	48	17.73
2013	May	185	158.2	76	30.74
2013	June	157.2	157	65	62.57
2013	July	154.9	143	68	63.69
2013	August	112.34	133	42	N/A
2013	September	77	98.7	17	17.87
2013	October	60.4	72.6	9	7.14
2013	November				
2013	December				
	Total	**930.64**	**951.50**	**325.00**	**199.74**

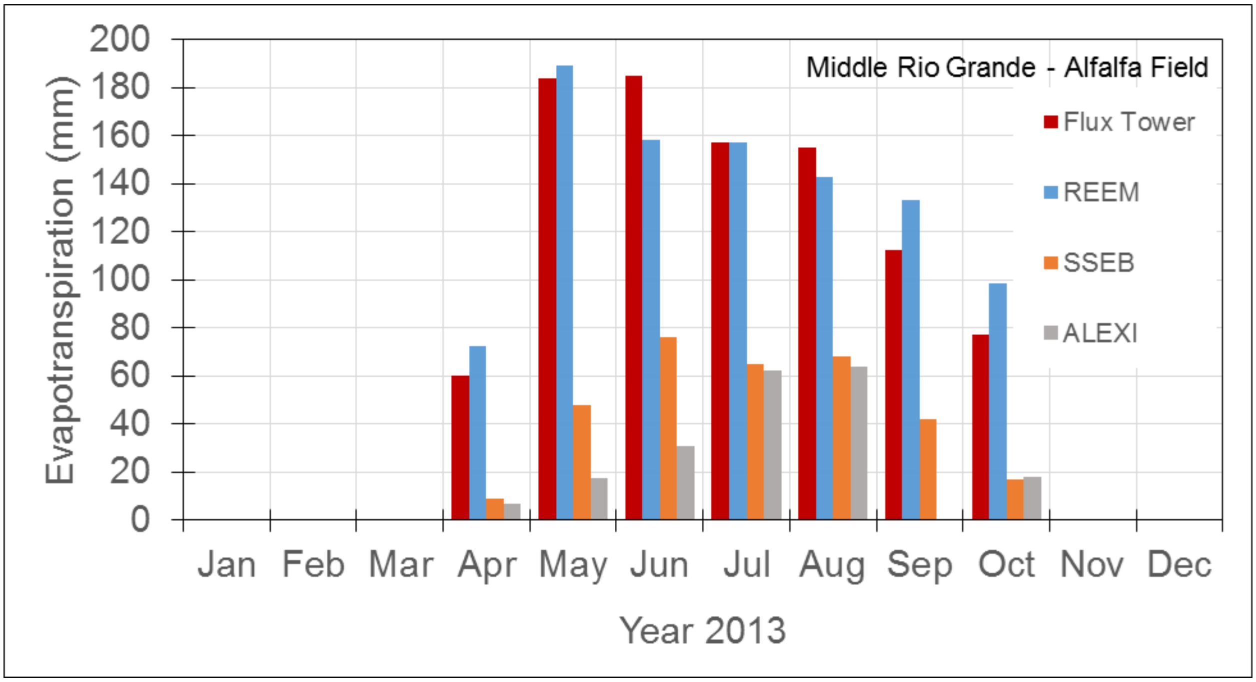

Figure 7. Monthly alfalfa evapotranspiration (ET) during growing season (April-October) for year 2013 as estimated by REEM, SSEB and ALEXI, and ground-measured Flux Tower

LRG Watershed ET Comparison

Using the shape file shown Figure 2, monthly ET was calculated using REEM and SSEB model. A comparison of monthly REEM and SSEB models for years 2011 and 2013 during the growing season from April through October are shown in Figures 8 and 9 for the MRG agricultural area. Growing season was selected due availability of satellite data during cloud free days. Growing season monthly ET values are presented in Table 6. Total growing season ET estimated for 2011 by REEM was 918.44 mm and SSEB 456.66 mm; a difference of 461.78 mm. In this case, SSEB estimate was 50% lower than the REEM. Growing season ET estimates of year 2013 was 607.35 mm and 730.22 mm for REEM and SSEB, respectively; a difference of 143.26 mm. The large difference in REEM simulated average ET of MRG between 2011 (918.44 mm) and 2013 (607.35 mm) was due to low allocation of surface water for irrigation in 2013 which was about 1/3 of 2011 allocation. The comparison of SSEB with REEM for 2013 was reasonably close but there was a significant difference in 2011. The low estimation by SSEB during 2011 can be attributed to general underestimation of ET during periods of high ET rates as was also observed in LRG.

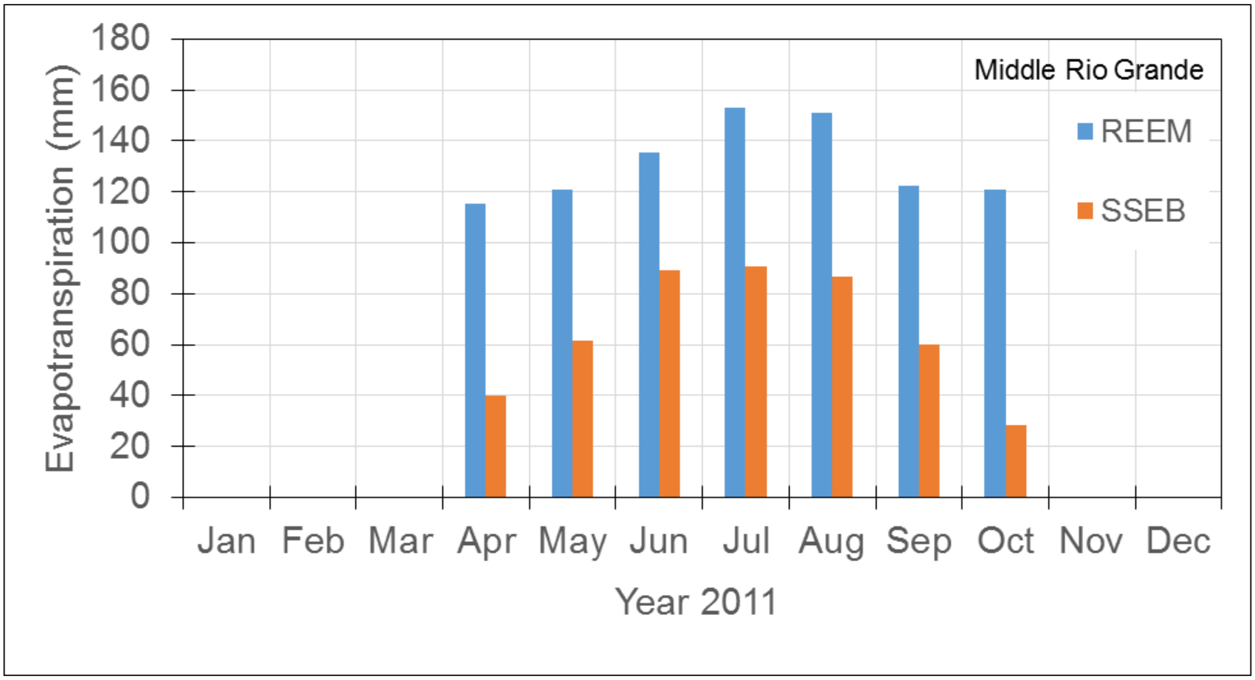

Figure 8. Growing season Middle Rio Grande (MRG) evapotranspiration (ET) estimated by REEM and SSEB for year 2011

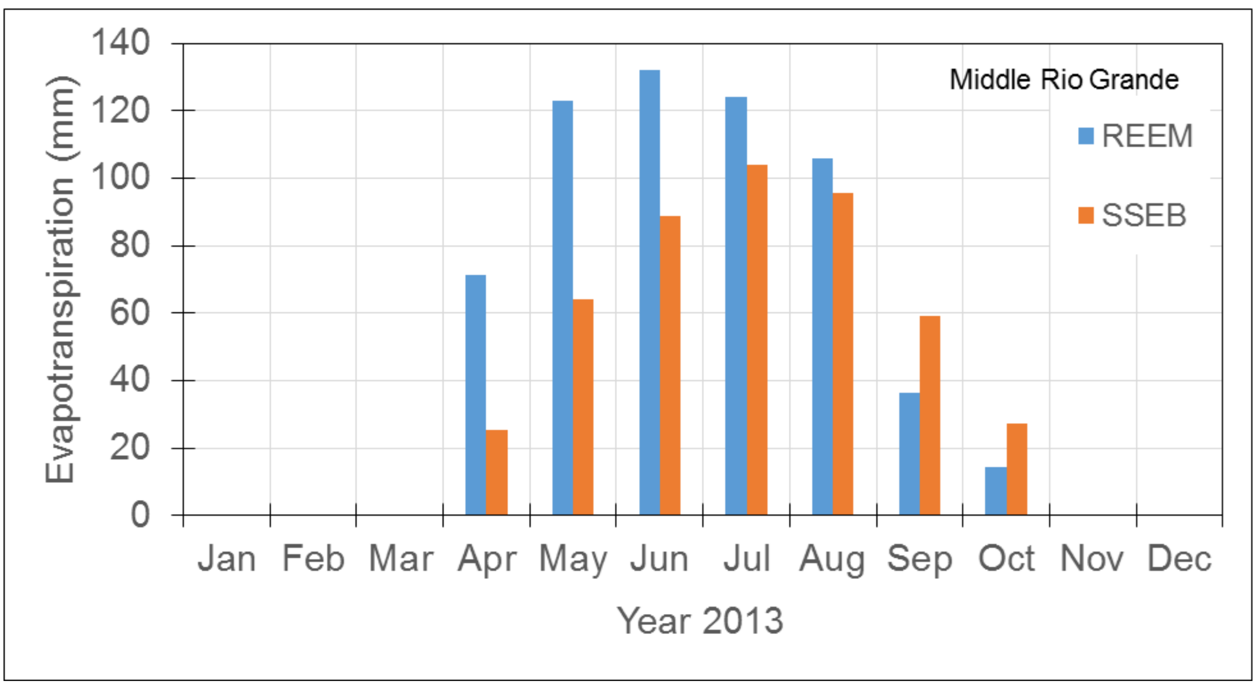

Figure 9. Growing season Middle Rio Grande (MRG) evapotranspiration (ET) estimated by REEM and SSEB for year 2013

Table 6. Middle Rio Grande (MRG) evapotranspiration estimates during growing season (April-October) for years 2011 & 2013

Year	**Month**	**Evapotranspiration (mm)**	
		REEM	**SSEB**
2011	January		
2011	February		
2011	March		
2011	April	115.20	40.05
2011	May	120.60	61.39
2011	June	135.60	89.41
2011	July	153.00	90.66
2011	August	150.90	86.76
2011	September	122.42	60.17
2011	October	120.72	28.22
2011	November		
2011	December		
	Total	**918.44**	**456.66**
2013	January		
2013	February		
2013	March		
2013	April	71.46	25.26
2013	May	123.00	64.02
2013	June	132.00	88.93
2013	July	124.00	103.96
2013	August	105.90	95.71
2013	September	36.50	59.09
2013	October	14.49	27.12
2013	November		
2013	December		
	Total	**607.35**	**464.09**

CONCLUSION AND RECOMMENDATION

Three remote sensing ET estimation models (REEM, SSEB and ALEXI) were evaluated and compared to ground-measured ET by Flux Towers. In this phase of proposed work, the model estimates for agricultural areas in the LRG and MRG were evaluated. The ALEXI model ET results were consistently very low and unrealistic when compared to the REEM and SSEB. One of the potential contributing factor in low ET estimates by ALEXI is the large pixel size (5 to 10 km) resolution where agricultural fields are surrounded by dessert environment.

The SSEB model estimates when compared to the Flux Tower measurements and REEM varied. In the LRG, the SSEB mature pecan annual ET estimates for 2008 were 31% and REEM 12% lower than the ground-measured ET. For the alfalfa comparison during the same period of 2008, the SSEB was 42% and REEM 12% lower than the Flux Tower. In the MRG, the SSEB growing season (April-October, 2013) alfalfa ET estimates were 65% lower and REEM 2% higher than the ground-measured Flux Tower. These preliminary results indicate that factors such as the resolution of the satellite images used in the models (5km, 1 km, 120 m, etc.), the algorithm used in determining components of the energy budget, and among other factors such as the land surface and atmospheric conditions may cause under or over estimation of ET. It was noticed that the SSEB model ET estimates for the LRG during 2008 was very similar to ET estimates by REEM; SEEB overestimated it by 7% when compared to REEM. This coincided with low irrigation water allocation within the LRG by Elephant Butte Irrigation District (EBID). The low water allocation of irrigation water caused the farmers within the LRG to leave their lands fallow or stress the plants while others augmented the surface allocated water with groundwater. In this condition, the SSEB model results were very similar to REEM. The SSEB model proves promising for regional ET estimation. It is recommended that the SSEB model be further evaluated and improved to estimate regional ET.

In general, SSEB model appears to calculate reasonable ET values when the ET rates are low but it underestimates the ET values when the rates are high. Our preliminary investigation has shown there is a potential to improve SSEB model to calculate accurate estimation of regional ET. For example, in one case in LRG, the corrected SSEB ET calculations compared to measured ET can be reduced from 40% to 10%.

REFERENCES

Allen, R.G., M. Tasumi, and R. Trezza. 2007a. Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC) – Model. *ASCE Journal of Irrigation and Drainage Engineering*. 133(4):380 – 394.

Amiro, B. D., and E.E., Wuschke. 1987. Evapotranspiration from a Boreal Forest Drainage Basin Using an Energy Balance/Eddy Correlation Technique. *Boundary-Layer Meteorology*. 38: 125 – 139.

Anderson, M. C., J. M. Norman, G. R. Diak, W. P. Kustas, and J. R. Mecikalski. 1997. A two-source time-integrated model for estimating surface fluxes using thermal infrared remote sensing. *Remote Sens. Environ*. 60: 195 – 216.

Anderson, M. C., J. M. Norman, G. R. Diak, J. A. Otkin, and W. P. Kustas. 2007a. A climatological study of evapotranspiration and moisture stress across the continental United States based on thermal remote sensing: 1. Model formulation. *J. Geophys. Res.* 112: D10117, doi: 10.1029/2006JD007506.

Bawazir, A. S. 2000. *Saltcedar and Cottonwood Riparian Evapotranspiration in the Middle Rio Grande*, Ph. D. diss. New Mexico State University, Las Cruces, New Mexico.

Bawazir, A. S., Samani, Z., Bleiweiss, M., Skaggs, R. and T.,Schmugge. 2009. Using ASTER satellite data to calculate riparian evapotranspiration in the Middle Rio Grande, New Mexico. *International Journal of Remote Sensing.* 30(21): 5593 – 5603.

Bastiaannsen W. G. M. 1995. Regionalization of surface flux densities and moisture indicators in composite terrain: a remote sensing approach under clear skies in Mediterranean climates. Ph.D. dissertation, Landbouwuniversiteit te Wageningen, the Netherlands. Published as report 109 of DLO Win and Staring Centre, Wageningen, The Netherland.

Blanford, J.H. and L.W. Gay. 1992. Tests of a robust eddy correlation system for sensible heat flux. *Theoretical and Applied Climatology.* 46:1:53 – 60.

Mecikalski, J. R., G. R. Diak, M.C. Anderson, and J. M. Norman. 1999. Estimating fluxes on continental scales using remotely-sensed data in an atmospheric–land exchange model. *J. Appl. Meteor*. 38: 1352 – 1369.

Norman, J. M., W. P. Kustas, and K. S. Humes. 1995. A two-source approach for estimating soil and vegetation energy fluxes from observations of directional radiometric surface temperatures. *Agric. For. Meteor.* 77: 263 – 293.

Norman, J.M., Anderson, M.C., Kustas, W.P., French, A.N., Mecikalski, J., Torn, R., Diak,G.R., Schmugge, T.J., Tanner, B.C.W. 2003. Remote sensing of surface energy fluxes at 101-m pixel resolution. *Water Resour. Res.* 39: 1221 – 1237.

Samani, Z., A. Bawazir, R. Skaggs, M. Bleiweiss, M. pinion, and V. Tran. 2007. Water use by agricultural crops and riparian vegetation: An application of remote sensing technology. *Journal of contemporary water research and education*: 137-8 – 13.

Samani, Z, S. Bawazir, Max Bleiweiss, Rhonda Skaggs, J. Longworth, Vien Tran, and Aldo Pinion. 2009. Using remote sensing to evaluate the spatial variability of evapotranspiration and crop coefficient in the lower Rio Grande Valley, New Mexico. *Irrig. Sci.* 28:93 – 100.

Senay, G.B., M.E. Budde, J.P. Verdin, and A.M. Melesse. 2007. A Coupled Remote Sensing and Simplified Surface Energy Balance (SSEB) Approach to Estimate Actual Evapotranspiration from Irrigated Fields. *Sensors.* (7)979 – 1000.

Senay, G.B., S. Leake, P.L. Nagler, G. Artan, J. Dickinson, J.T. Cordova, and E.P. Glenn. 2011b. Estimating Basin Scale Evapo-transpiration (ET) by Water Balance and Remote Sensing Methods. *Hydrological Processes*. 25: 4037 – 4049.

Senay, G.B., S. Bohms, R.K. Singh, P.H. Gowda, N.M. Velpuri, H. Alemu, and J.P. Verdin. 2013. Operational evapotranspiration mapping using remote sensing and weather datasets: A new parameterization for the SSEB approach. *J. Am. Water Resourc. Assoc*. 49: 577 – 591.

Singh, R., G. Senay, N. Velpuri, S. Bohms, R. Scott, and J. Verdin. 2014. Actual Evapotranspiration (Water Use) Assessment of the Colorado River Basin at the Landsat Resolution Using the Operational Simplified Surface Energy Balance Model. *Remote Sensing*. *6*(1): 233 – 256.