QUANTIFICATION OF WATER FLUXES AND IRRIGATION USE THROUGH REMOTE SENSING

FINAL REPORT

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Problem Statement:

Irrigation accounts for 80% of fresh water use in the U.S. and worldwide, the World Bank estimates 70% of fresh water use is for agriculture. The U.S. irrigates over 50 million acres of agricultural land and 32 million acres of recreational landscapes. In Oklahoma, irrigation is the largest water use accounting for 72% of Oklahoma's groundwater withdrawal (OWRB, 2007). The hydrologic conditions in irrigated areas of Oklahoma dictate that irrigation pumped from aquifers, and to a limited degree, streamflow, must supplement, or entirely satisfy the crop water requirements of cotton, com, wheat, soybeans, or other crops. As the Ogallala aquifer declines and climatic variability affects water supply from reservoir storage, resource conflicts will arise that exacerbate the difficult allocation of insufficient water resources. Evapotranspiration (ET) estimation from agricultural areas is important to water resource management as irrigation consumes the largest share in water use, globally as well as in Oklahoma. Without direct measurement of ET, only indirect computations based on a hydrologic water balance can identify the transport of water to the atmosphere. An additional difficulty arises when ET estimation is computed from atmospheric variables, because such measures represent potential ET and not actual ET. Traditional ET estimation methods typically provide potential or reference ET at points and do not contain information on the geographic variation of ET. Recent advances in satellite remote sensing of ET have opened frontiers in water management at local, regional, and global scales. Integrating satellite data with available ground based measurements by using a Simplified Surface Energy Balance (SSEB) method renders opportunities to utilize remote sensing data products for sustainable water management. This project has integrated MODIS (Moderate Resolution Imaging Spectroradiometer) and ground-based data to estimate actual ET for monitoring water use in agricultural areas and water flux from urban areas and lakes.

Currently, the Oklahoma Climate Survey OCS (Mesonet, 2007) estimates daily grass reference ET at each Mesonet site and interpolates the point values to entire state. Weakness of the ET Model is that it estimates reference ET not actual ET, and that the estimates are sparsely located across the State. The model applied by OCS assumes a uniform crop coefficient of 1.0 that is not representative of the diversity of plant types in an irrigated area or watershed, thus unable to obtain actual ET to account for spatial variability of water deficit/surplus. Second, both crop coefficients and actual *ET* are inherently variable because of crop variety, irrigation methods, weather, soil types, salinity and fertility, and/or field management that can be very different from the field used to derive the reference values. This project advances our understanding over previously established methods for estimating water flux because the ET measurement is distributed spatially and temporally, and is directly attributed to actual rather than potential water flux.

Project Objectives:

The theory and robustness of using of remote sensing for ET estimation has been demonstrated through the combination of SSEB and MODIS data products. Remote sensing ET algorithms mainly solve the Surface Energy Balance (SEB) of the land surface for latent heat flux (LE) at the time of satellite overpass. The central scientific basis of SEB methods is to compute the LE as the residual of the energy balance equation which is the approach taken in the proposed scope that follows. Remote sensing ET algorithms mainly solve the Surface Energy Balance (SEB) of the land surface for latent heat flux (LE) at the time of satellite overpass.

Through quantification of the water fluxes, actual ET and precipitation (P), we will validate the method for the expanded study areas. Once validated with eddy flux measurements, we will develop high resolution maps of water flux, aET - P, and examine the spatial trends and seasonality of water use associated with irrigation in agricultural and urban areas. Towards the goal of extending our study activities, we have planned three phases:

1. Agricultural irrigation evaluation. Evaluation of the ET estimation accuracy will be accomplished in two agricultural counties, Texas and Jackson (Lugert-Altus) where irrigation demand for water resources is high. The two counties represent two distinctly different geographic locations in terms of climate, 10 inches of precipitation in Texas County, and 36 inches annually in Jackson. An improved remote sensing ET algorithm will be calibrated and validated to provide actual ET estimates for monitoring irrigation water usage taking into account the specific study area precipitation, climate and cropping practices.
2. River basin and selected reservoir water flux estimation. We will compute actual ET and water fluxes for purposes of refining our algorithm for the lake and river basin study area.
3. Water fluxes in the urban areas of Oklahoma City and Tulsa.

Students supported by this program

Student Status	Number	Disciplines
Undergraduate	0	
M.S.	1	Civil Engineering/Water Resources Engineering
Ph.D.	1 (partial support)	Geography
Post Doc	0	
Total	2	

Methodology:

Water is taken up by plants and crops and transpired to the atmosphere through evapotranspiration, also called consumptive use. Knowing how much water evaporates from land surfaces to atmosphere can help in estimating water use and availability for water planning purposes. Actual evapotranspiration (aET) can be measured through remote sensing derived from the NASA/MODIS satellite and ground measurements. Traditional evapotranspiration (ET) estimation methods such as pan or atmospheric measurements usually provide potential ET at specific points, but not as spatially distributed ET. Further, these methods only provide potential ET (pET) and not actual ET (aET), which is limited by availability of soil moisture or free water. The robustness of aET estimation using remote sensing is demonstrated with application to irrigation water use in Oklahoma including Texas County, metropolitan areas, and the Altus-Lugert Irrigation District.

Principal Findings and Significance:

Water fluxes for irrigated areas of Texas County and Lugert-Altus Irrigation District, for urban areas of Tulsa City, Oklahoma City and for Lake Thunderbird and Texoma were successfully estimated over a two year period, 2007-2008. Using MODIS data and precipitation data, irrigation water use was computed for Texas County, Lugert-Altus District, Oklahoma City area and the City of Tulsa. In Texas County, it was found that about 127,892 ac-ft and 49,171 ac-ft were used respectively in 2007 and 2008. The wide variation is due to differences in precipitation for the two years in irrigated areas of the county. In the Lugert Altus District, irrigation water use was estimated to be 37,072 ac-ft and 42,438 ac-ft, respectively for 2007 and 2008. Water flux over urban areas in 2008 was found to be 29.53 inches in Tulsa, and 32.34 inches in Oklahoma City in 2007, and 34.75 inches and 40.94 inches. The validation of the results found that the accuracy of the method produced reasonable amounts of water flux that compared well with pan evaporation and crop water usage.

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1. Introduction

As demand for water increases, water managers need to know how much water is actually consumed in agriculture. This knowledge can help in the reduction in agricultural water use in areas of scarce supplies so that water can be released for other uses. Critical to any irrigation management approach is an accurate estimate of the amount of water applied to a field. Various ways are used for such estimation. Some methods use the water balance approach and others base their approach on the flow rate, the total time of irrigation and the area irrigated. The flow rate, total time of irrigation and the area irrigated approach using Equation (1):

$$Q \times t = d \times A \qquad (1)$$

Where **Q** is the flow rate, in cubic feet per second (cfs), **t** is the set time or total time of irrigation (hours), **d** is the depth of water applied (inches) and **A** is the area irrigated (acres). However, because irrigation water, Q, may not be adequately metered at all farms, indirect methods of estimating water use would be attractive. The approach used in this study, the water balance approach, accounts of the inputs and outputs of water over a specified area, whether it is an agricultural field, watershed, or continent, the water balance can be determined by calculating the input, output, and change in storage of water at the Earth's surface. The general water balance equation is shown as Equation (2) :

$$P - R - E - T - G = \Delta S \qquad (2)$$

Where **P** is the Precipitation, **R** is the Runoff, **E** is the Evaporation, **T** is the Transpiration, **G** is the Groundwater and, **ΔS** is the change in storage. Evaporation and Transpiration can be combined to evapotranspiration (ET). This study uses precipitation and evapotranspiration for the water balance approach to quantify the water fluxes and irrigation use. In fact, the major input of water is from precipitation, and output is evapotranspiration in the study areas. Different methods have been developed to estimate evapotranspiration from remote sensing data. In this study, ET has been calculated using a model that was developed called Mesonet/Modis ET (M/M-ET) described by Khan et al. (in press).

1.1. Statement of Critical Regional and State Water Problem

Throughout the world, irrigation is one of the largest consumers of water. Almost 60 percent of all the world's freshwater withdrawals go towards irrigation uses (USGS, 2010). In many Western States, agriculture accounts for 80 percent of the Nation's consumptive water use and over 90 percent of ground and surface water (ERS/USDA, 2004). In Oklahoma, after public water supply that counts for 41% of total of water use, irrigation accounts for 32%. Groundwater is a predominant source, and accounts for 73 percent of total irrigation water use in Oklahoma (OWRB, 2010). Climatic conditions in irrigated areas of Oklahoma dictate that irrigation water pumped from aquifers and to a limited degree, streamflow, is used to supplement or entirely satisfy the crop water requirements of cotton, corn, wheat, soybeans, and other high value crops. Knowledge of crop water use in high-use areas provides useful planning information for water planning, especially in Texas County supplied by the Ogallala Aquifer (High Plains), and in the Lugert-Altus Irrigation District, and water flux in urban areas. Understanding water use in these areas is critical to understanding where water is consumed in the state, and supports planning efforts.

1.2. Study Background

1.2.1. Remote Sensing: A Good Way To Quantify Water Fluxes and Irrigation

Remote sensing can assist in improving the estimation of the distribution of evapotranspiration. Consequently, it can help in a sustainable water resources management in large cultivated areas for irrigation purposes. Evapotranspiration is one of the main components of the water cycle. However, its estimation is difficult to achieve in practice because actual evapotranspiration cannot be measured directly and varies considerably in time and space. A large number of empirical methods have been developed over the last 50 years worldwide to estimate evapotranspiration from different climatic and meteorological variables (Tsouni et al. 2008).

1.2.2. Previous Study

Actual evapotranspiration can be measured from remotely sensed images from the NASA satellite derived estimates as demonstrated in the current study. Evapotranspiration is among the most important processes in the hydrologic cycle and considered as a critical component in diverse disciplines such as those involved in water resource management, agriculture, ecology, and climate science. Estimation of spatially distributed ET from agricultural areas is important as irrigation consumes the largest share in water use (Glenn et al., 2007; Shiklomanov, 1998). It has been found that in arid and semi arid biomes, around 90% or more of the annual precipitation can be evapotranspired, and thus ET determines the freshwater recharge and discharge from aquifers in these environments (Huxman et al. 2005). Moreover, it is projected that climate change will influence the global water cycle and intensify ET globally (Meehl et al., 2007; Huntington et al., 2006), consequently impacting the scarce water resources.

Similarly, reliable ET estimates are crucial for efficient use of water resources, especially in agricultural areas for water management (Gowda et al., 2008; Bouwer et al., 2007). Methods of ET estimation provide potential or reference ET. Sometimes crop ET is derived as a product of weather based reference ET and crop coefficient (Kc) at points, rather than spatiotemporal information about actual ET (Allen et al. 2005).

Satellite remote sensing for ET estimation has become a pragmatic approach, due to the availability of remote sensing data and development of various modeling techniques. Because remotely sensed data have the advantage of a large area coverage, frequent updates and consistent quality, remote sensing based ET estimation has been a subject of many studies (Jackson, 1986; Kuittinen, 1992; Kite and Pietroniro, 1996; Stewart et al. 1999; Rango and Shalaby, 1998; Mu et al. 2007; Sobrino et al., 2007; Santanello et al., 2007; Wang et al., 2007). Although several recent ET models only use remote sensing data for ET estimation (Jiang et al., 2004; Nishida et al., 2003; Norman et al., 2003), integrating meteorological field observations and remote sensing data with optimum spatial and temporal resolution can overcome many of the shortcomings associated with low spatial coverage of field scale models and low temporal resolution of satellite data products. Cost effectiveness and easy implementation can be an added advantage. Thus, over the years various ET models have been developed that use the remote sensing and ancillary surface and ground-based observations (Choudhury, 1994; Seguin, 1994; Jiang and Islam, 2001; Senay et al., 2007). Surface Energy Balance Algorithm for Land (SEBAL) is described in Bastiaanssen et al.1998, 2005 and later METRIC (Mapping EvapoTranspiration with high Resolution and Internalized Calibration) is an ET estimation model developed and applied by the University of Idaho, USA (Allen et al. 2007). Subsequent applications in ET estimation have opened frontiers in agricultural water use and groundwater resources management at different scales and in diverse climates.

These developments in remote sensing of ET have been applied in the western U.S. and many other parts of the world (Allen et al., 2007). However, most of previous applications have been retrospective in nature (Tang et al., 2009) in part because of the lack of the timely availability of satellite images in relatively frequent revisit frequency, e.g. Landsat 16-day. Furthermore, many in-situ ground observations do not provide data in real-time or with sufficient update frequency. Although the retrospective ET estimates can be useful in modeling studies, they cannot aid operational water management decision-making in real-time.

With the availability of MODIS products twice-daily and well-distributed environmental monitoring stations from the Oklahoma Mesonet that has a 5-minute acquisition frequency, Oklahoma provides a unique setting to develop and application of satellite-based ET estimation. For the past decades, the primary method for estimating ET relied on site-based weather station measurements, which are inadequate to monitor the spatial variability of ET over large regions and only focus on potential rather than actual ET. Therefore, we focus on estimation of daily actual ET on a large scale in Oklahoma and apply it to understanding water use and fluxes from urban areas, and lakes.

1.3. Study Area

There are six areas in Oklahoma considered in this study. They are 1) Texas County, 2) Altus-Lugert Irrigation District, 3) City of Tulsa, 4) Oklahoma City, 5) Lake Thunderbird, and 6) Lake Texoma. The location of these study areas are shown in Figure 1. A range of climatic conditions are represented among the study areas with Texas County and the Lugert-Altus Irrigation District located in arid conditions where potential ET greatly exceeds actual ET making irrigation necessary for most crops. While Tulsa is the farthest east with a subhumid climate, potential ET still exceeds actual ET.

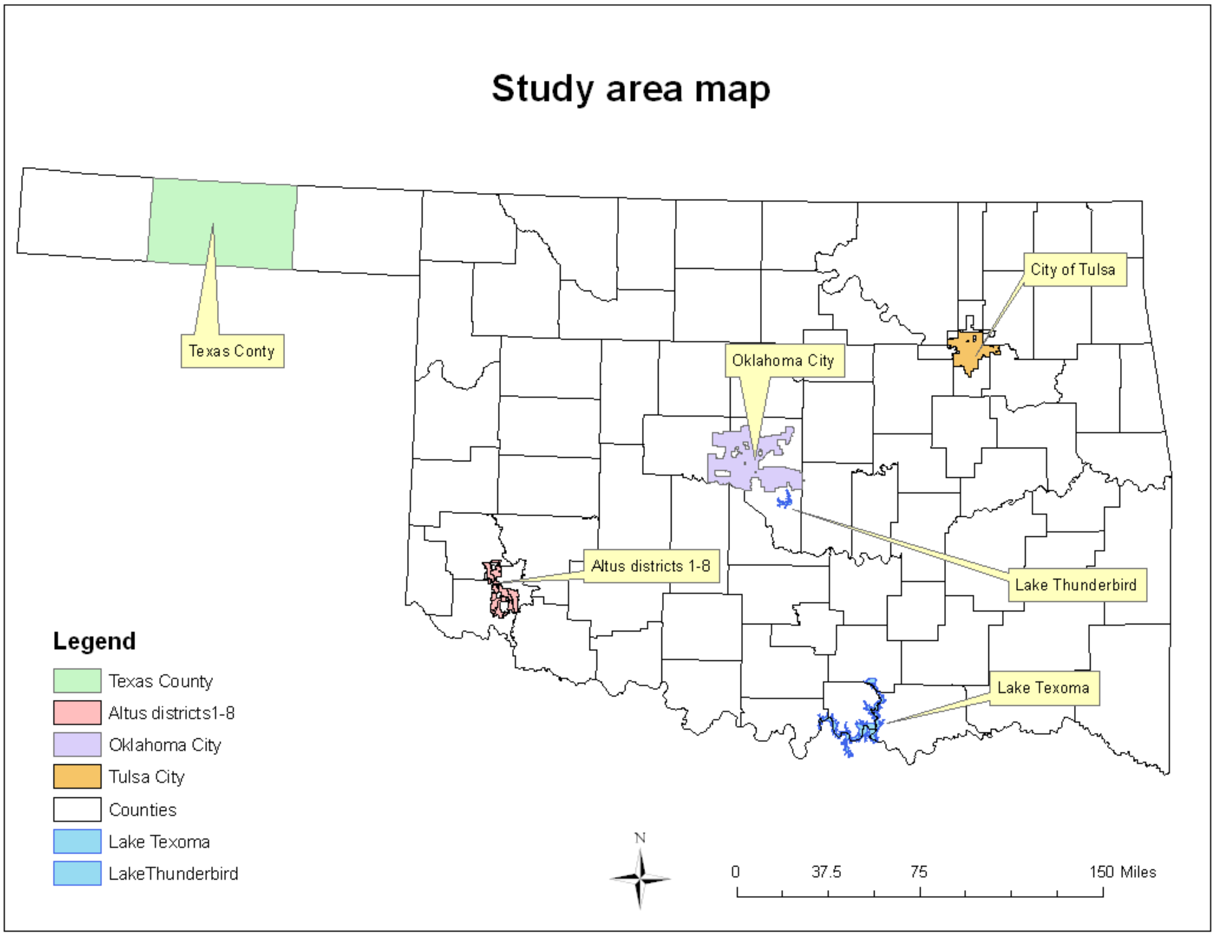

Figure 1: Map of Oklahoma showing study areas

1.3.1. Texas County

Agriculture in Texas County is largely supported by irrigation from the Ogallala Aquifer. The average farm size is 1179 acres. About 23.43% of the land in these farms is harvested cropland with 55.02% as irrigated harvested cropland of land in farms. The majority of the farms, 84.93%, are operated by a family or individual. The National Agricultural Statistics Service (NASS) estimates that there were 81,633 acres of corn harvested for grain, 179,027 acres of wheat harvested for grain, and 45,244 acres of sorghum harvested for grain, in 2007 in Texas County. (USDA/NASS, 2009)

1.3.2. Altus-Lugert District

The Lugert-Altus Irrigation District, also known as W. C. Austin Project, was completed in 1946 by the Bureau of Reclamation (BOR) for irrigation, flood control, municipal water storage, fish and wildlife conservation and recreational benefits. Altus Lake, which serves as the source of water to the District, has a contributing drainage area of 2,515 sq. miles. It receives its waters from the North Fork of the Red River and its tributaries. Three principal canals – the West canal, the Ozark canal, and the Altus canal along with their laterals, distribute water from the Altus Lake to approximately 500 diversions points. Water released through these canals is tabulated and was used in this analysis. Water flows throughout the District by gravitational flow, crossing the North Fork of the Red River and several state highways through siphons. The District is subdivided into eight sub-districts, called ditchrider-districts. The OWRB (2001a) study focused on districts 1 to 8 and estimates the canal losses and other hydrologic quantities. The irrigated area of the District is approximately 26 miles long by 14 miles wide (OWRB, 2001a). The irrigated area varies from year to year depending crops planted; however, the geographic area used in this study for computation of irrigation water use is estimated to be 89,817acres (OWRB, 2001a).

1.3.3. Urban Areas of Oklahoma City and Tulsa

The metropolitan area of Oklahoma City is a large urban region located in the central part of the state of Oklahoma. It contains the state capital and principal city, Oklahoma City and covers seven counties. The Tulsa Metropolitan Area is located in Northeastern Oklahoma. The area used in this analysis consists of the corporate boundaries for the two metropolitan areas from the Center of Spatial Analyst of the University of Oklahoma (CSA), which were estimated with ArcGis to be 397,908 and 128,782 acres for Oklahoma City and Tulsa, respectively (CSA, 2010).

1.3.4. Lake Texoma

Lake Texoma is one of the largest reservoirs in the United States, the 12th largest Corps of Engineers (USACE) Lake. Lake Texoma is formed by Denison Dam on the Red River in Bryan County, Oklahoma, and Grayson County, Texas, about 726 miles upstream from the mouth of the river. It is located at the confluence of the Red River and Washita Rivers. The dam site is approximately 5 miles northwest of Denison, Texas, and 15 miles southwest of Durant, Oklahoma. The drainage area above the dam of the watershed is 39,719 square miles. While the lake surface area can vary due to inflow and releases from the reservoir, however, the area considered in computation of lake evaporation was estimated with ArcGis as 59,015 acres, corresponding to normal pool elevation for its Oklahoma part (OWRB, 2004).

1.3.5. Lake Thunderbird

Lake Thunderbird, located in Cleveland County in central Oklahoma, serves as a water supply for the City of Norman, Midwest City, and Del City. The Norman Dam was constructed in 1965 and is managed by Central Oklahoma Master Conservancy District. Lake Thunderbird has 76,648 acre feet of capacity assigned to flood control and surcharge capacity of 171,300 acre-feet. The 2001 bathymetric survey conducted by the OWRB determined Lake Thunderbird to have a maximum depth of 58 feet, mean depth of 15.4 feet, surface area of 5,439 acres and volume of 105,838 acre-feet (OWRB, 2001b).

2. Methodology

2.1. Study Dataset

Data required for computation of actual ET include MODIS sensor data, Mesonet measurements of potential ET, and rainfall. The rainfall data is spatially distributed estimates produced from radar and rain gauge and is generated from the ScourCast system operated for the Oklahoma Department of Transportation (Vieux, 2008). Additionally, land cover data, pan evaporation data from COMCD, and study area boundaries were assembled to accomplish the analysis required for this study.

2.1.1. Rainfall Data

The rainfall data was produced by the ScourCast system, which performs continuous distributed watershed model simulation and rainfall monitoring for bridges that are subject to scour. ScourCast provides continuous rainfall at 2x2 km resolution and at 15-minute updates, and made available for this study. A radar mosaic is formed from 13 S-band radars and operational gauge-correction using 120 rain gauges as shown in Figure 2 below.

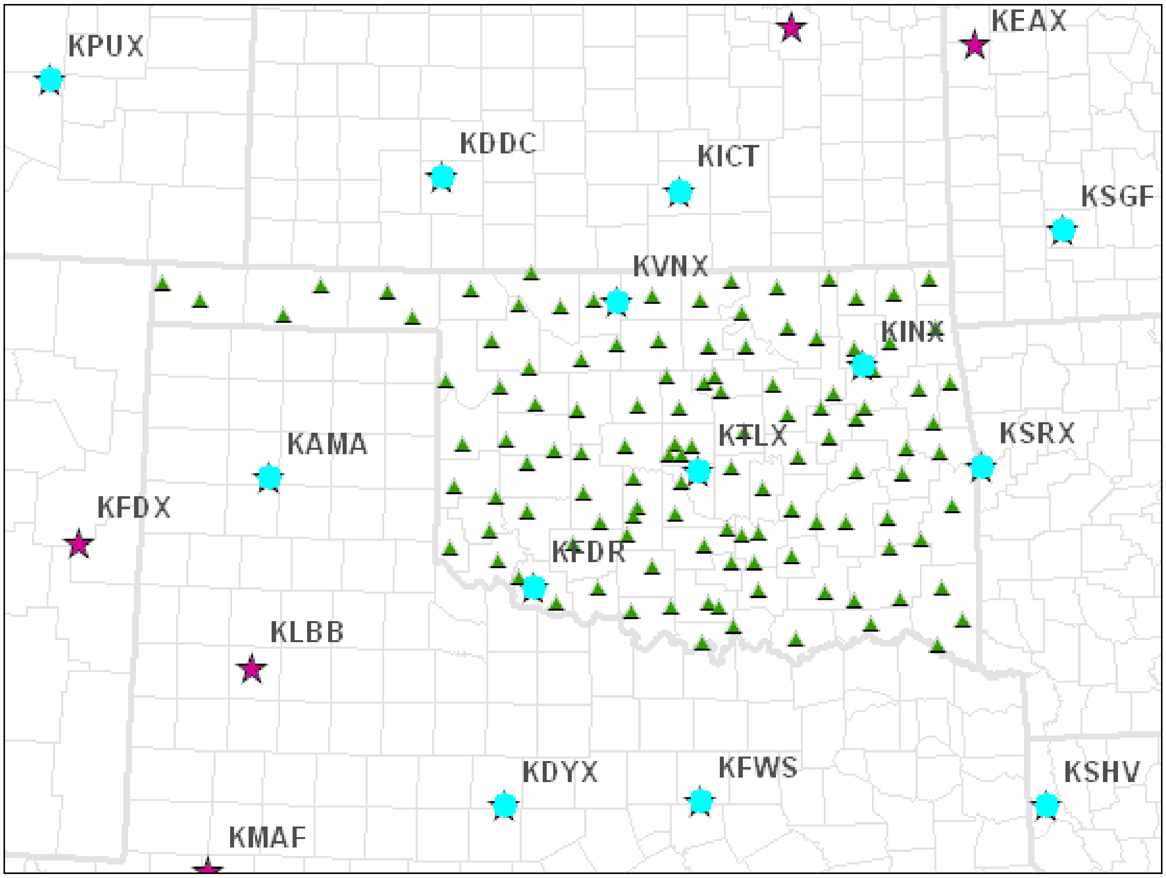

Figure 2: ScourCast observational network composed of 13 NWS Radars and 120 Oklahoma Mesonet Rain Gauges

2.1.2. Land Cover

The land cover data includes the National Land Cover Dataset (NLCD) from USGS Land Cover Institute and Cropland Data Layer (CDL) from National Agricultural Statistics Service (NASS) on USDA data gateway (USDA, 2010). The National Land Cover Database 2001 (NLCD, 2001) was compiled across all 50 states and Puerto Rico as a cooperative mapping effort by USGS. This land cover database has been created using mapping zones and contains standardized land cover components. The NLCD layer has sixteen classes of land cover that were modeled over the conterminous United States at a 30m cell size with a 1 acre minimum mapping unit. This dataset is used in this study to calculate actual evapotranspiration. Figure 3 shows the Anderson Classification scheme for the state of Oklahoma.

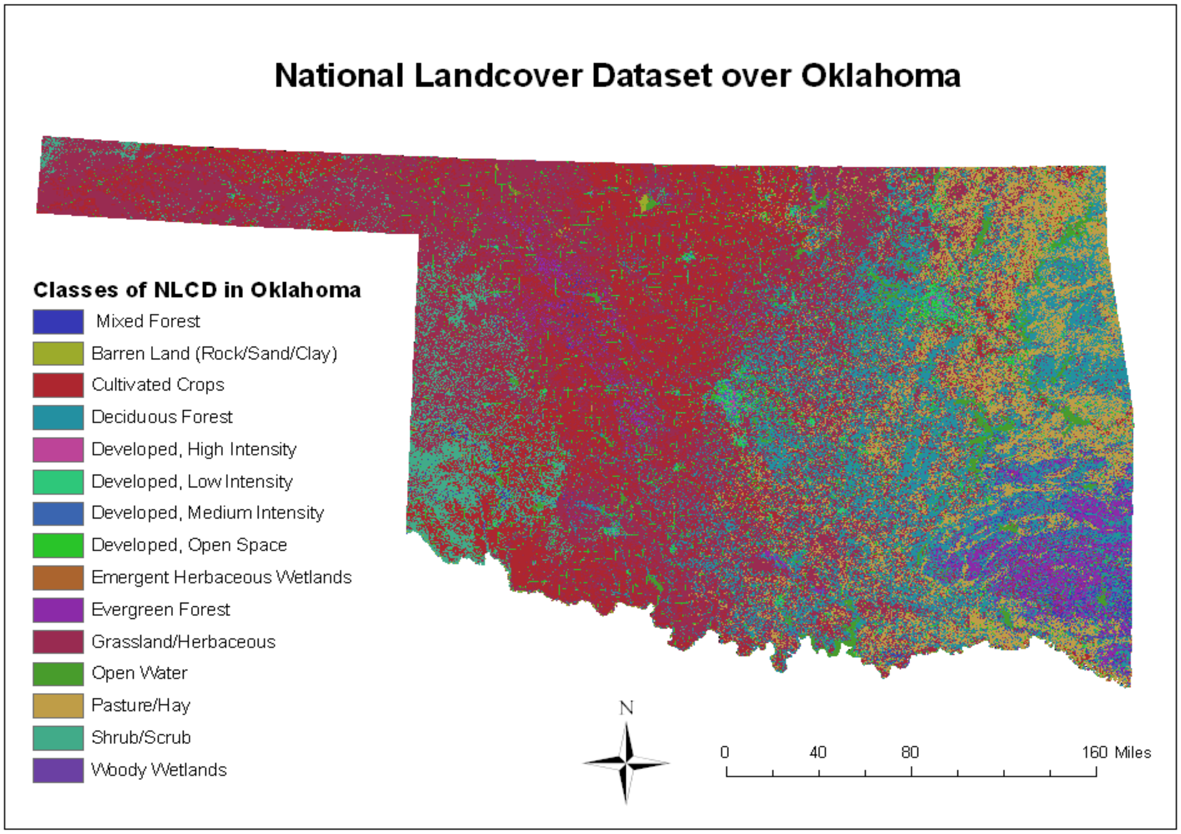

Figure 3: National Land Cover Dataset over Oklahoma

Each year, USDA develops a Cropland Data Layer built upon the NASS traditional crop acreage estimation program, and integrates collected ground survey data with satellite imagery to create an unbiased statistical estimator of crop area at the state and county level. The CDL was used in this study to identify irrigated areas during the study years of 2007 and 2008. The CDL for Oklahoma is shown in Figure 4 for the year 2007.

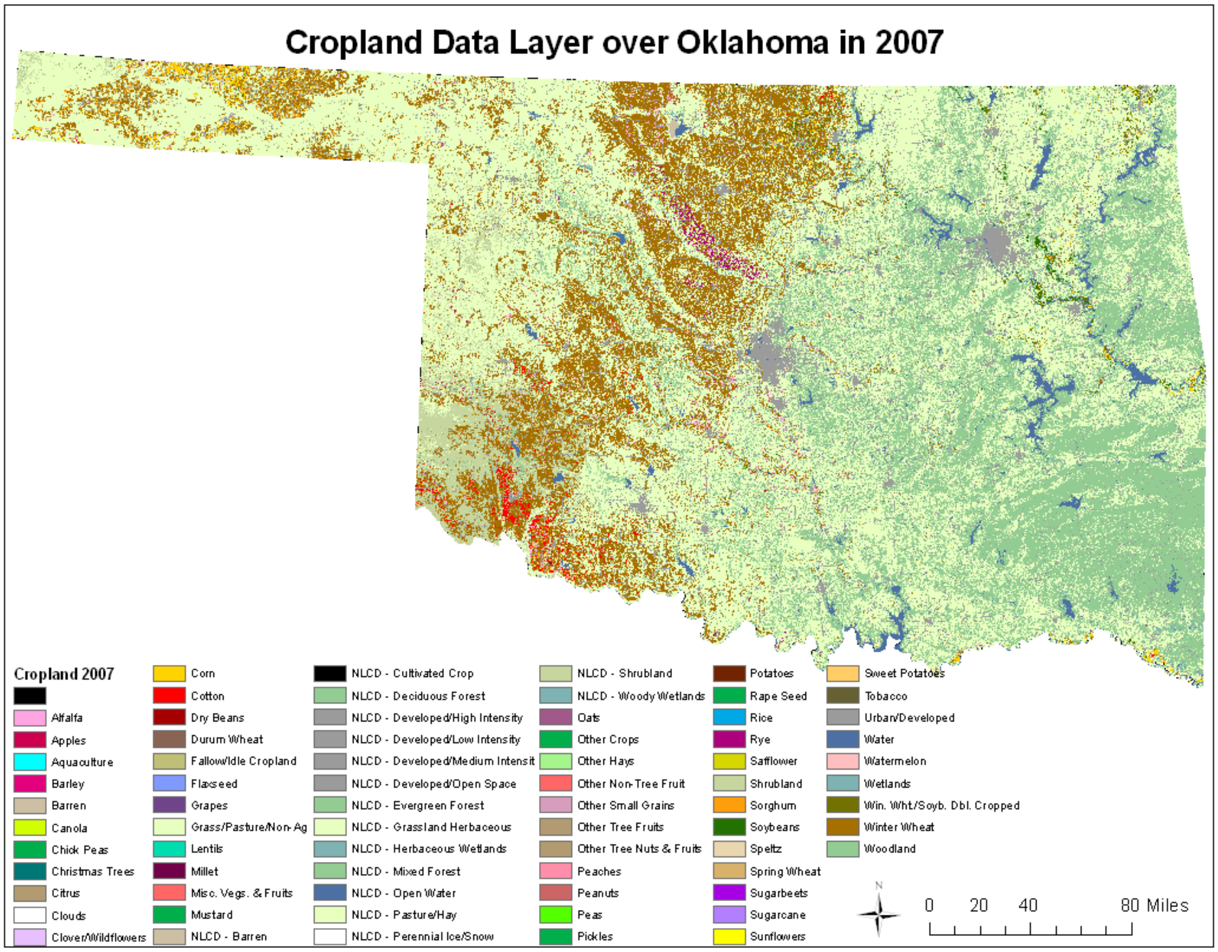

Figure 4: Cropland Data Layer over Oklahoma in 2007

2.1.3. Oklahoma Meteorological Observations: Mesonet

The Oklahoma Mesonet is a network of environmental monitoring stations jointly managed by the University of Oklahoma (OU) and Oklahoma State University (OSU). Established as a multipurpose network, it operates more than 120 automated surface observing stations covering the state of the Oklahoma and measures comprehensive meteorological, hydrological, and agricultural variables since the early 1990’s. These monitoring sites have collected over 3,750,000,000 observations since January 1st, 1994 (McPherson et al., 2007). At each site, the environment is measured by a set of instruments located on or near a 10-meter-tall tower. The measurements are packaged into "observations" every 5 minutes; then the observations are transmitted to a central facility every 5 minutes, 24 hours per day year-round. The Oklahoma Climatological Survey (OCS) at OU receives the observations, verifies the quality of the data and provides the data to Mesonet customers. It only takes 5 to 10 minutes from the time the measurements are acquired until they become available to the public.

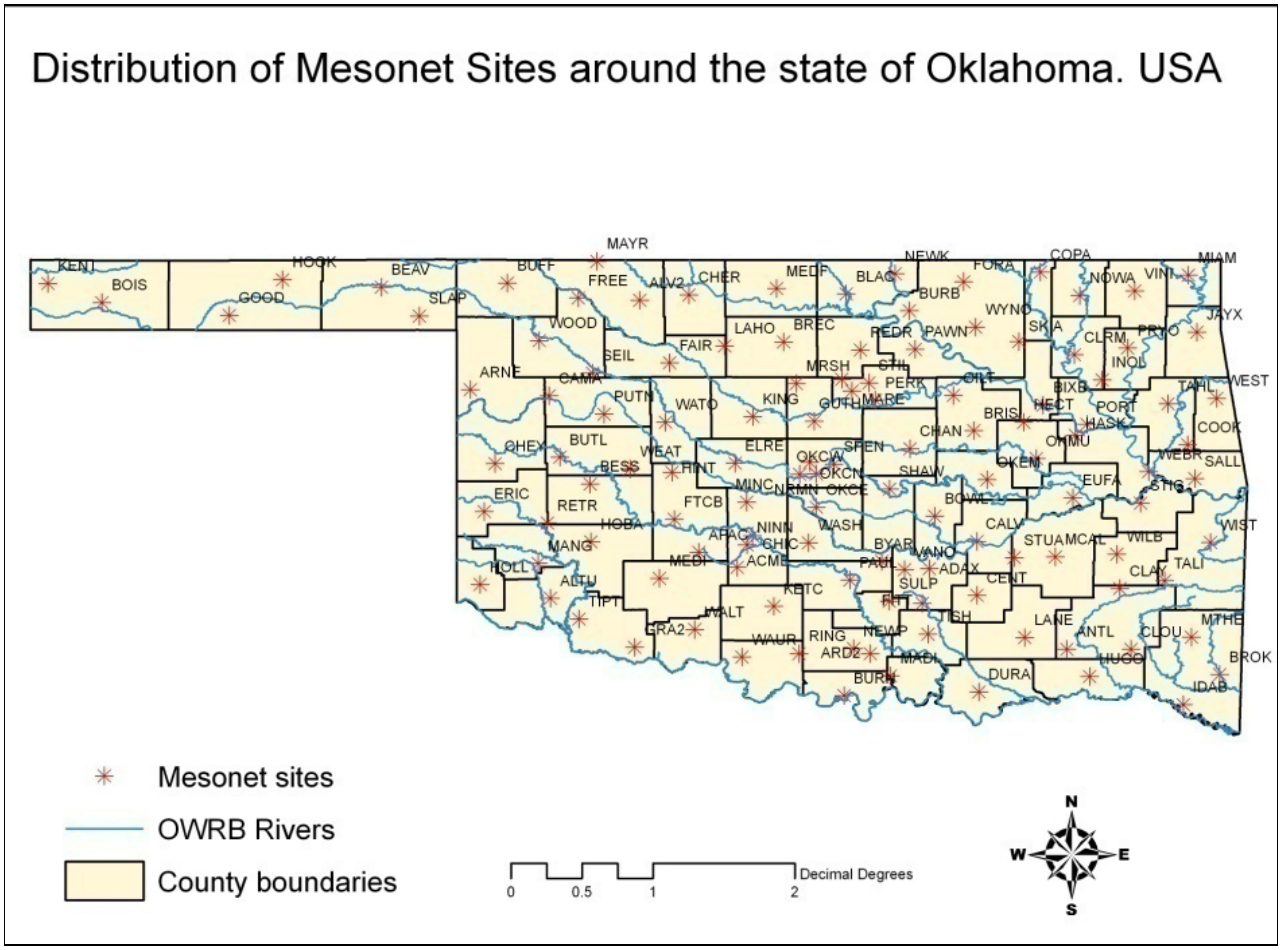

Figure 5: Oklahoma Mesonet monitoring stations (red asterisks) with station ID's.

2.1.4. Satellite Remote Sensing Data

The MODIS sensors, with 36 spectral bands (20 reflective solar and 16 thermal emissive bands), provide information regarding vegetation and surface energy (Justice et al. 2002), which can be used to develop a remotely sensed ET model (Mu et al. 2007). ET-relevant MODIS data used in this study are listed in (Table 2). Wan and Li (1997) described the retrieval of MOD11 land surface temperature (LST) and emissivity from MODIS data. Detailed information about MOD09 surface reflectance products is provided in Vermote et al. (1997) and Xiong et al. (2007). The algorithm for retrieving the Vegetation Index (MOD13) is presented by Huete et al. (2002). The computation of broadband Albedo (MOD43B3) by integrating bi-hemispherical reflectance data modeled over MODIS channels 1-7 (0.3-5.0 um) is explained in Schaaf et al. (2002). All NASA MODIS land products include so called Quality Assessment Science Data Sets (QA-SDS), which considers the atmospheric conditions in term of cloud cover and aerosol content, algorithm choices, processing failure, and error estimates (Colditz et al. 2006). These data products were extracted and processed from the Land Processes Distributed Active Archive Center (LP DAAC) at the USGS EROS Data Center, with the standard Hierarchical Data Format (http://LPDAAC.usgs.gov).

Table 1: ET-Relevant NASA MODIS data products

Product ID	Layer	Spatiotemporal resolution	MODIS QA-SDS[a] Analysis (Quality flags passed)
MOD11A2	Land Surface Temperature (LST) Emissivity View Angle Recording time	1-km[b], overpass 1-km, overpass 1-km, overpass 1-km, overpass	General quality: good
MOD13Q1	Vegetation index NDVI	1-km, 16-day	quality: good ~ perfect mixed clouds: no
MOD43B3	Albedo	1km, 16-day	Quality: good and acceptable Snow: no
MOD09Q1	Red reflectance NIR reflectance	250m, 8-day	Quality: good Clouds: clear Band quality: highest
MOD15A2	Leaf Area Index (LAI)	1km, 8-day	Quality: good Cloud: clear or assumed clear
MOD12Q1	Land Cover Type	250m, annual	Quality: good

[a]*Quality Assessment Science Data Sets*
[b]*The swath products were gridded using the MODIS reprojection tool (MRT)*
[c]*The view angles were analyzed to remove effects from scan geometry caused by increasing IFOV towards the edges of the scan lines*

2.1.5. Study Areas Boundaries

The study area's boundaries were downloaded on the Center for Spatial Analysis of the University of Oklahoma (CSA) website. These boundaries were downloaded as shapefiles that can be added to ArcGis.

2.2. Data Processing

2.2.1. Rainfall Data

The rainfall data have been processed from 15 minutes incremental timesteps and aggregated to daily and monthly using Matlab scripts and mapped with ArcGis. The maps of precipitation are then sampled within the same geographic coordinate system as the aET.

2.2.2. Reference Evapotranspiration and Actual Evapotranspiration

Khan et al., 2009 developed the Mesonet/Modis-ET (M/M-ET) algorithm, which solves the Surface Energy Balance (SEB) of the land surface for latent heat flux (LE) at the time of satellite overpass and extrapolate instantaneous LE to daily ET values. The central scientific basis of SEB methods is to compute the *LE* as the residual of the energy balance equation:

$$LE = R_n - H - G \qquad (3)$$

Where the available net radiant energy, Rn (Wm^{-2}), is shared between the soil heat flux G and the atmospheric convective fluxes, sensible heat flux H and latent heat flux LE, which is readily converted to ET. The Rn and other components (H and G) of SEB can be derived through remote sensing information and surface properties such as albedo, leaf area index, vegetation cover, and surface temperature (Ts). The following components of energy balance were solved and are explained here.

2.2.2.1 Net Radiation (Rn)

Rn is computed by subtracting all outgoing radiant fluxes from all incoming radiant fluxes and includes solar and thermal radiation. This is shown as Equation 4.

$$R_n = RS\downarrow - \alpha RS\downarrow + RL\downarrow - RL\uparrow - (1 - \varepsilon_o)RL\downarrow$$

(4)

Where RS↓=incoming short-wave radiation (Wm^{-2}); α=surface albedo (dimensionless); RL↓=incoming long-wave radiation (Wm^2); RL↑=outgoing long-wave radiation (Wm^2); and εo=broad-band surface thermal emissivity (dimensionless). The (1 −εo) RL↓ term represents the fraction of incoming long-wave radiation reflected from the surface.

2.2.2.2 Soil Heat Flux (G)

Soil Heat Flux (G) is the rate of heat storage in the soil and vegetation due to conduction. General applications compute G as a ratio G/Rn using an empirical equation by Bastiaanssen (2000) representing values near midday as shown in Equation 5.

$$G = (Ts - 273.16)\ (0.0038 + 0.0074\alpha)\ (1 - 0.98\text{NDVI}^4)\ R_n \qquad (5)$$

Where Ts is surface temperature (K), and α is the surface albedo. The Normalized Difference Vegetation Index (NDVI) is used to predict surface roughness and emissivity.

2.2.2.3 Sensible Heat Flux (H)

Sensible Heat Flux (H) is defined by the bulk aerodynamic resistance equation, Equation 6, which uses aerodynamic temperature (T_{aero}) and aerodynamic resistance to heat transfer (r_{ah}):

$$H = \rho_{air}\ Cpa\ (T_{aero} - Ta)\ /\ rah \qquad (6)$$

In the bulk aerodynamic resistance equation, ρ_{air} is air density (kg m^{-3}), Cpa is specific heat of dry air (1004 J kg^{-1} K^{-1}), Ta is average air temperature, (K), T_{aero} is average aerodynamic temperature (K), which is defined for a uniform surface as the temperature at the height of the zero plane displacement (d, m) plus the roughness length (Zoh, m) for sensible heat transfer, and rah is aerodynamic resistance (s m^{-1}) to heat transfer from Zoh to Zm [height of wind speed measurement (m).

2.2.2.4 From instantaneous ET_i to daily accumulated ET

At the instant of the satellite image, Latent Heat (LE) is calculated for each pixel from Equation (3-6) and is converted to instantaneous ET (ET_{inst}) in mm h^{-1} by dividing LE by latent heat of vaporization, Equation 7:

$$ET_{inst} = (3600 \times LE) / (\lambda\ \rho_w) \qquad (7)$$

Where ρ_w=density of water (~1000 kg m-3); 3,600 converts from seconds to hours; and latent heat of vaporation (J kg^{-1}) representing the heat absorbed when a kilogram of water evaporates and is computed using Equation 8.

$$\lambda = [2.501 - 0.00236 \times (Ts - 273.15)] \times 10^6 \qquad (8)$$

Reference ET fraction (ETrF) is the ratio of ET_{inst} to the reference ETr that is defined by the American Society of Civil Engineers and can also be computed using the standard Penman-Monteith alfalfa reference method (ASCE-EWRI, 2005) at overpass time (hourly average). Finally, the computation of daily or 24-h ET (ET_d), for each pixel, is performed with the following, Equation 9.

$$ET_d = ETrF \times ETr \times 24 \tag{9}$$

3. Results

The estimation of water fluxes was based on actual ET and precipitation. This section gives the results for actual ET, precipitation, and actual ET minus precipitation. Details are provided below concerning estimated water fluxes for Texas County, Lugert-Altus Irrigation District, Oklahoma City, City of Tulsa and Lake Texoma.

3.1. Actual Evapotranspiration

Actual evapotranspiration was calculated annually for both years 2007 and 2008 and also monthly. Figure 6 is the map of actual evapotranspiration for 2007 for the entire state of Oklahoma.

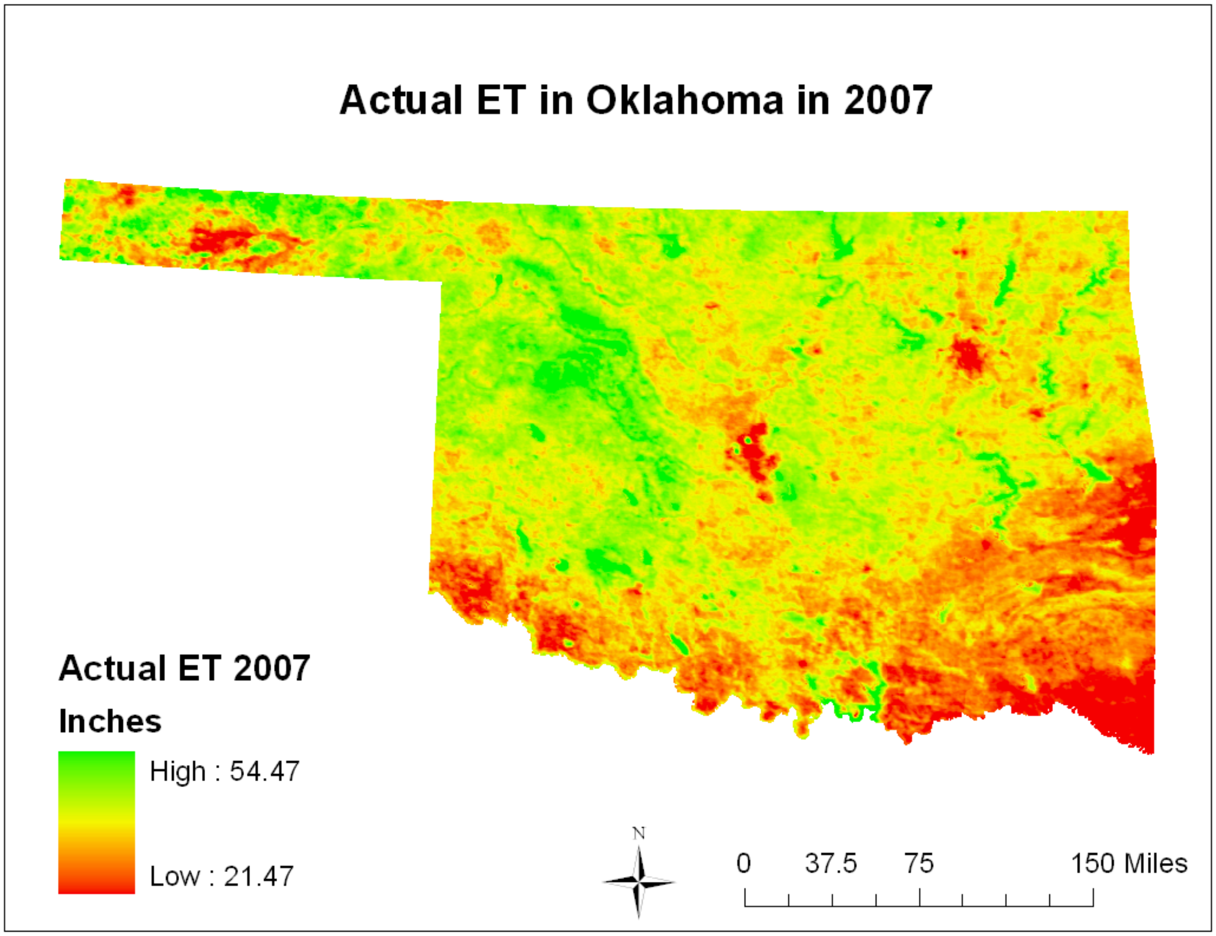

Figure 6: Annual Actual Evapotranspiration map in 2007

3.2. Precipitation

Precipitation was also calculated annually for both years 2007 and 2008 as well as monthly. Figure 7 shows the annual precipitation in Oklahoma for 2007.

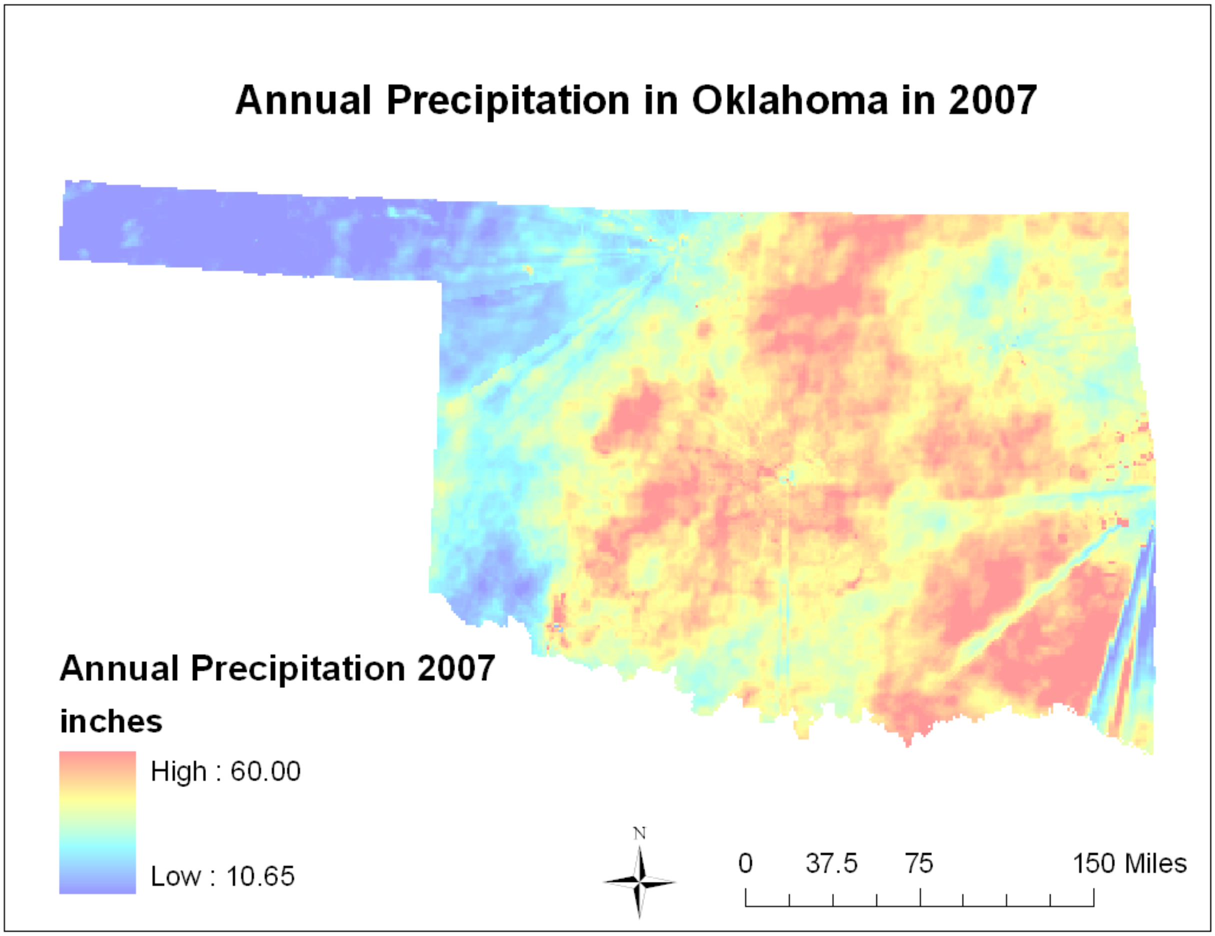

Figure 7: Annual Precipitation map in 2007

3.3. Actual evapotranspiration minus Precipitation

Actual evapotranspiration minus precipitation which is the estimation of water use for irrigation has been calculated annually as well as monthly. Figure 8 shows the annual difference between actual evapotranspiration and precipitation in Oklahoma in 2007.

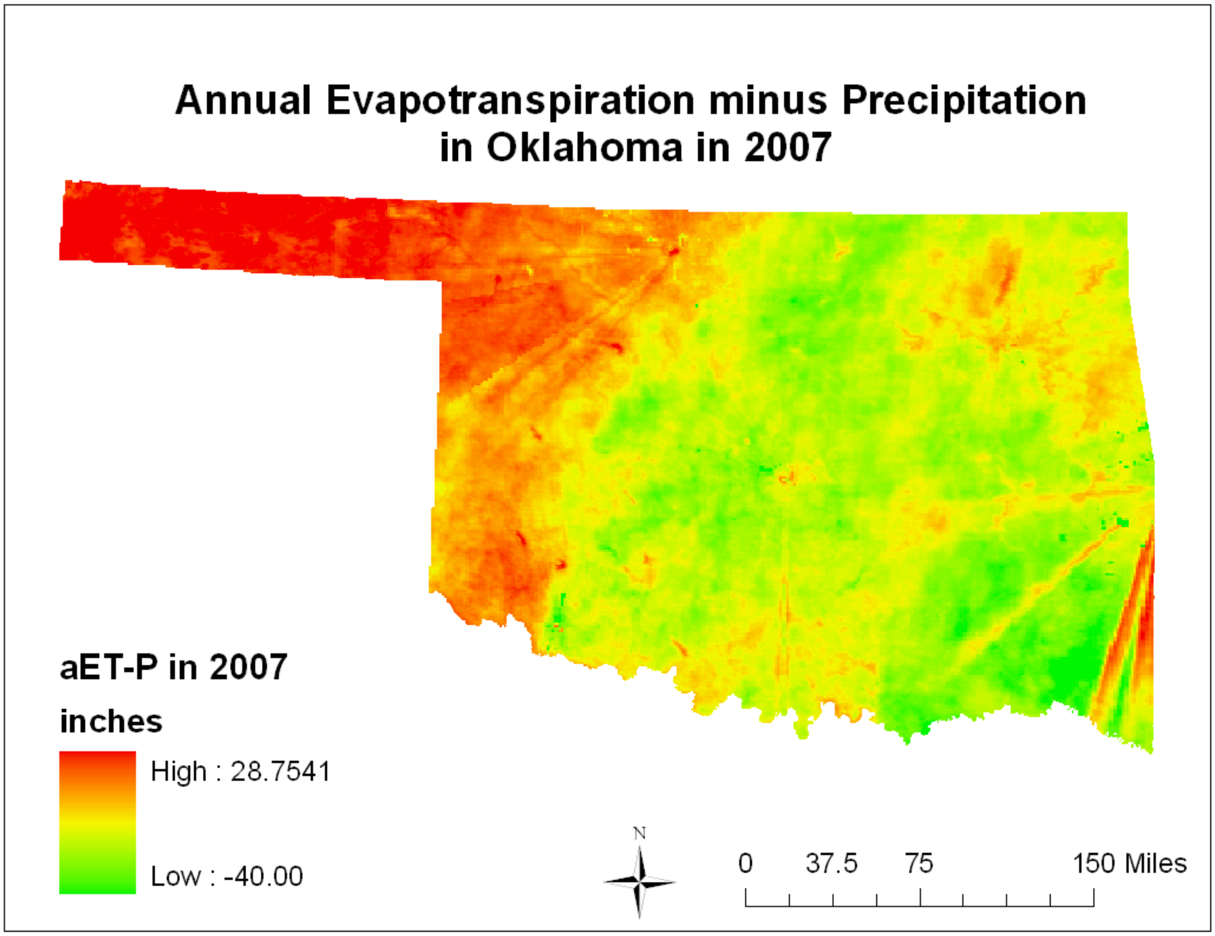

Figure 8 : Annual aET-P in Oklahoma in 2007

3.4. Major Crops

The cropland data layers derived from the NASS (2007 and 2008) geospatial data mentioned above were used for comparison of estimated and expected crop water use. Each year, the type of crop, its geographic extent and location is mapped using remotely sensed information. The difference between actual ET and precipitation (aET-P) is estimated for the crops using NASS data. Because of the arid climate in Texas County no runoff is expected, and therefore, aET-P is considered as crop water use. The aET-P water flux is extracted over each crop type contained in the NASS data for both Texas County and Altus-Lugert District.

The major crops grown in Texas County for 2007 and 2008 were winter wheat, corn and sorghum. While in the Altus-Lugert District, cotton and winter wheat were the major crops for this study period. Table 2 presents the major crop categories listed for the two study areas, Texas County and Altus-Lugert, during

2007 and 2008, along with each crop expressed as a percentage of total irrigated cropland reported by NASS.

Table 2: Major crops and percentage of irrigated areas in Texas County and Altus-Lugert District

	Altus-Lugert		Texas County	
	Crops	% of total irrigated	Crops	% of total irrigated
2007	**Cotton**	**54.40**	**Winter Wheat**	**60.19**
	Winter Wheat	**41.71**	**Corn**	**23.20**
	Sorghum	2.07	**Sorghum**	**14.45**
	Alfalfa	1.59	Alfalfa	1.26
	W. Wheat / Soyb Dbl.	0.10	Soybeans	0.43
	Millet	0.05	Oats	0.30
	Peanuts	0.05	Sunflowers	0.09
	Oats	0.03	Other Small Grains	0.05
			Barley	0.03
			Millet	0.01
2008	**Cotton**	**61.27**	**Winter Wheat**	**66.34**
	Winter Wheat	**37.44**	**Corn**	**19.18**
	Alfalfa	0.50	**Sorghum**	**12.67**
	Sorghum	0.40	Alfalfa	1.54
	W. Wheat/Soy. Dbl. Crop	0.37	Cotton	0.09
	Corn	0.03	Soybeans	0.09
			Sunflowers	0.04
			Rye	0.03
			Other Small Grains	0.02

The growing seasons for these crops are referenced in Appendix A. Table A-1 refers to the growing season of Altus District and Table A-2 to the growing season of Texas County. Only cotton and winter wheat were considered to be irrigated in Altus-Lugert District while winter wheat, corn and sorghum were considered to be irrigated in Texas County.

3.5. Estimation of Water Fluxes and Irrigation Water Use

3.5.1. Texas County

The estimation of irrigation water use based on aET-P is summarized in Table 3 for 2007 and Table 4 for 2008. Figure 9 shows the percentage of water used for irrigation per crop in Texas County in 2007.

Winter Wheat was found to transpire large quantities throughout its growing season from October to May in Texas County. During the year there is water flux from soil moisture and not irrigation water application during the Fall, Winter and Spring seasons. Table 3 presents growing season water use excluding winter wheat in the total water use.

Table 3: Summary of water use, aET-P, for Texas County in 2007

Annual aET-P for Texas County in 2007		
Crops	**Growing Season Acre-ft**	**Growing Season Inches**
Winter Wheat	264,118	14.79
Corn	78,927	11.47
Sorghum	48,965	11.42
Sum major crops (Excluding Winter Wheat)	127,892	22.89

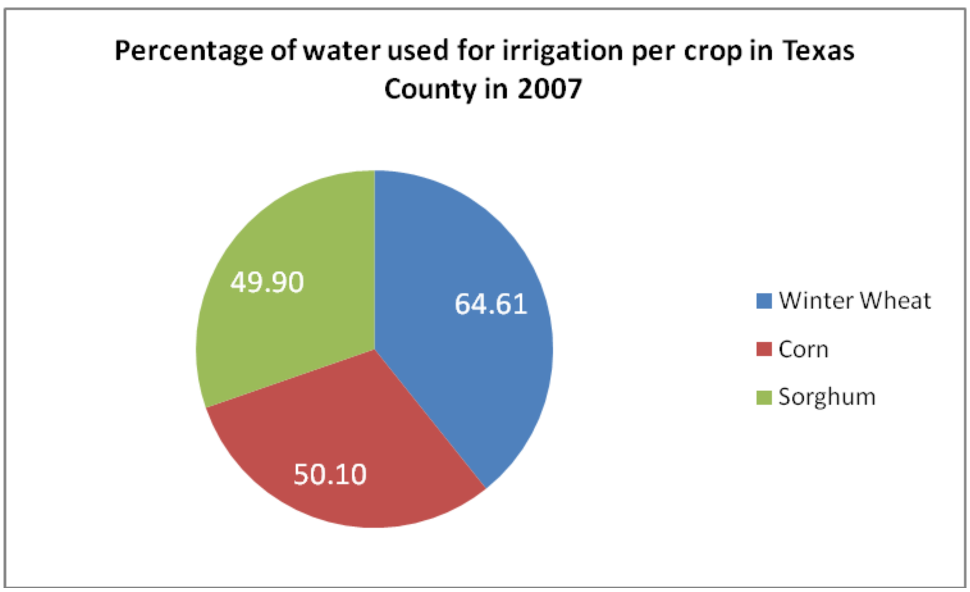

Figure 9: Percentage of water used for irrigation per crop in Texas County in 2007

Table 4: Summary of Results for 2008 for Texas County

Annual aET-P for Texas County in 2008		
Crops	**Growing Season Acre-ft**	**Growing Season Inches**
Winter Wheat	248,713	17.83
Corn	36,858	9.14
Sorghum	12,313	4.62
Sum major crops (Excluding Winter Wheat)	49,171	13.76

Appendix B contains graphs of the variation of aET-P over the entire period of study for Texas County and Altus-Lugert District. Figure B-10 shows aET-P variation in Texas County for the study period while Figure B-11 shows aET-P variation in Altus for the study period. Volume and depth differ because cropland area varies during the season.

3.5.2. Lugert-Altus District

The estimation of irrigation water use (aET-P) in 2007 and 2008 within Lugert-Altus in Districts 1 through 8 is summarized in Table 5. For the Lugert-Altus Irrigation District, only winter wheat and cotton were considered to be irrigated because they are the two major crops in the district. Contrary to Texas County, winter wheat was found to transpire a considerable amount in Lugert-Altus District during the growing season and so is included in the total estimated water use.

Table 5: Summary of Results for 2007 and 2008 for Altus-Lugert District

	Annual aET-P for Altus-Lugert in 2007 and 2008				
	Crops	**Growing Season Acre-ft**	**Growing Season Inches**	**Total Year Acre-ft**	**Total Year Inches**
2007	Winter Wheat	11,893	5.19	27,118	11.84
	Cotton	25,179	8.43	36,626	12.26
	Sum Major Crops	37,072	13.62	63,744	24.11
2008	Winter Wheat	17,071	8.59	27,348	13.76
	Cotton	25,367	7.80	47,843	14.71
	Sum Major Crops	42,438	16.39	75,190	28.47

3.5.3. Oklahoma City

From urban areas, aET is expected to be derived from a variety of sources, i.e. soil moisture, precipitation, groundwater, water bodies and irrigation of lawns. Even though the sources of aET cannot be separated, precipitation and aET are related. Table C-1 and Table C-2 of Appendix C shows monthly totals of these two components of the water balance for 2007 and 2008 respectively while Figure 10 shows the variation of aET, reference ET and precipitation over Oklahoma City (OKC). The values of actual ET, precipitation (precip) and reference ET (ref ET) are also recorded in Appendix C in Table C-3. The aET from OKC does not reach to full potential evapotranspiration represented by the reference ET. There were 1,072,314 ac-ft, or 32.34 inches of measured aET in 2007 and 1,357,565 ac-ft, or 40.94 inches of measured aET in 2008, which is less than reference by 47%, on average over 2007 and 2008. Actual ET for Oklahoma City does not exceed precipitation except for a few months in 2007 and 2008, because there is not sufficient irrigation of lawns to cause aET to exceed P.

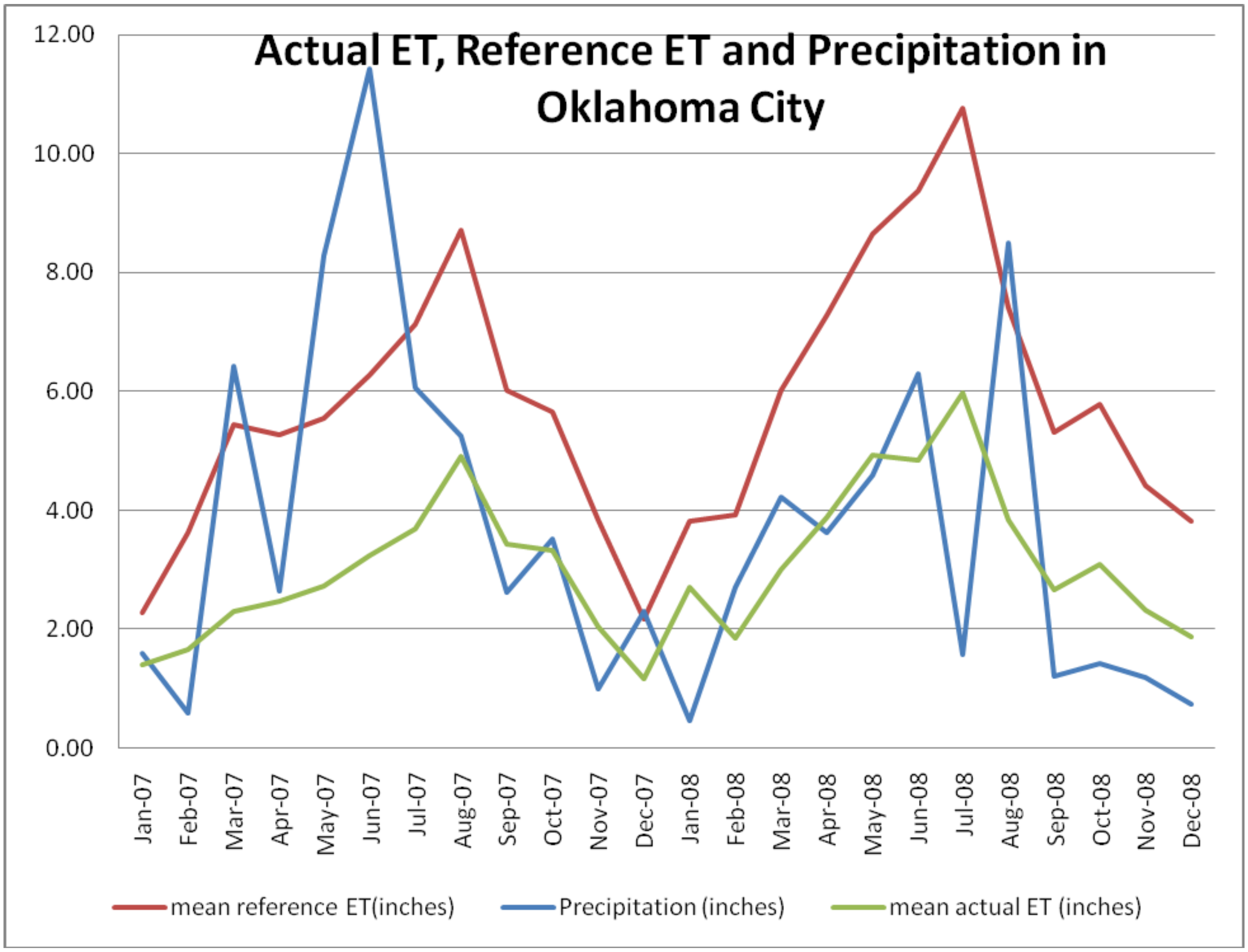

Figure 12: Precipitation, Actual ET, Reference ET in Oklahoma City area

3.5.4. Tulsa

As for Oklahoma City, values of aET were studied for water fluxes in Tulsa. Table D-1 and Table D-2 in Appendix D show monthly totals of these two components of the water balance for 2007 and 2008, respectively. Figure 11 shows the variation of aET, reference ET and precipitation over Tulsa. The values of actual ET, precipitation and reference ET are also recorded in Table D-3 of Appendix D. Similar to Oklahoma City, the aET from Tulsa does not reach to full potential evapotranspiration represented by the reference ET. There were 3,171,391 ac-ft, or 29.53 inches of measured aET in 2007 and 3,731,297 ac-ft, or 34.75 inches of measured aET in 2008, which is less than reference by 46.08%, on average over 2007 and 2008. The water flux from aET for the City of Tulsa does not exceed precipitation on an annual basis. During 2007 and 2008, aET exceeded precipitation in July and August, which may be attributed to lawn irrigation and possibly antecedent moisture from previous rainfall.

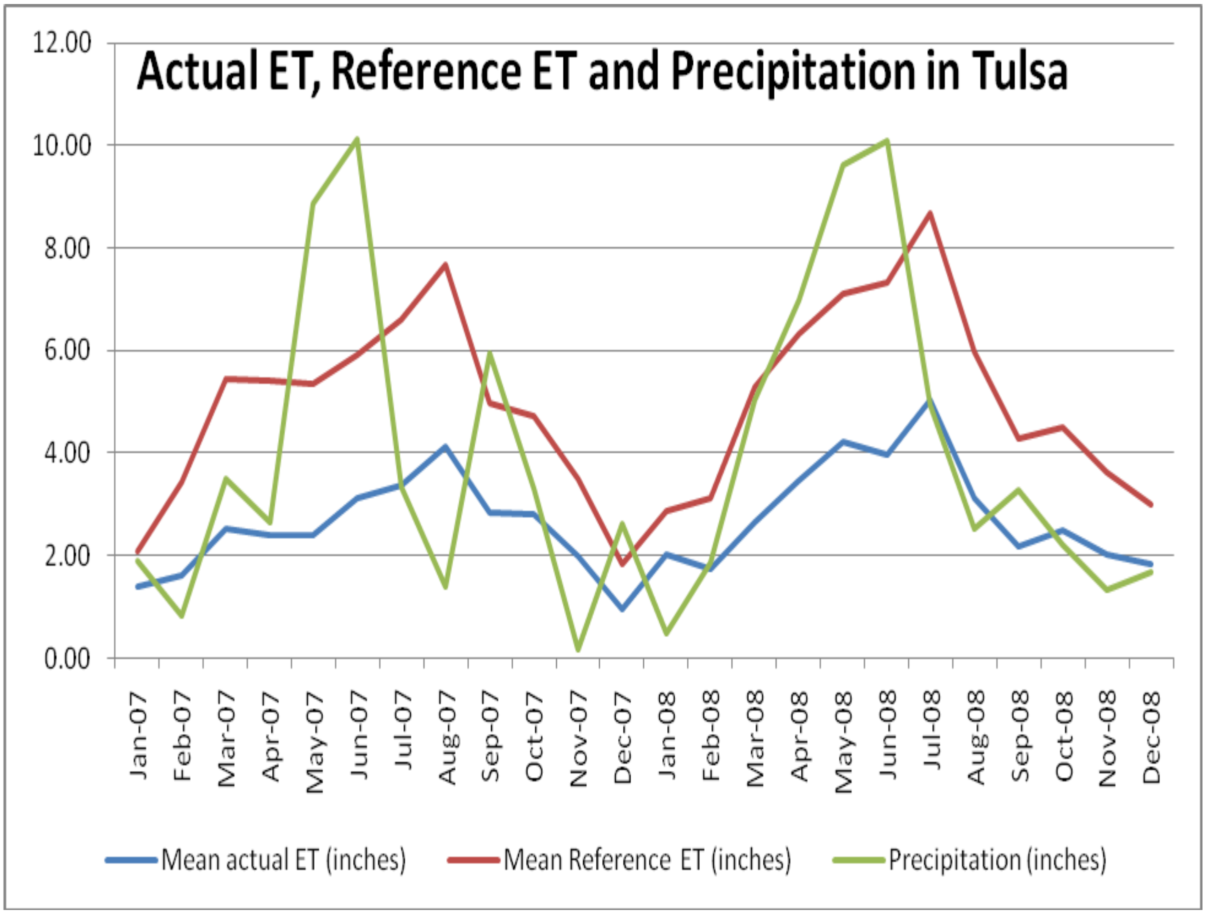

Figure 13: Precipitation, Actual ET, Reference ET in Tulsa area

3.5.5. Lake Texoma

Using the same methods for estimating aET from cropland (M/M-ET), the lake evaporation was estimated. The entire lake area is 84,428 acres, whereas, 58,931 acres are in Oklahoma. In the part of the lake in Oklahoma, the lake evaporation is 39.31 inches for 2007, and 49.43 inches for 2008.

Comparing reference ET and lake evaporation, lake evaporation is 0.65 of reference ET, which is consistent with pan coefficients reported by Farnsworth and Thompson (1982) and Bedient et al. (2009, p. 42). Table E-1 of Appendix E summarizes evaporation data in Lake Texoma.

4. VALIDATION OF RESULTS

4.1. Precipitation

The validation of the results includes validation of rainfall and validation of actual ET. To validate rainfall, national service data were used and compared to the processed one from ScourCast. The validation can be done by checking and comparing the precipitation record for the whole study period by ScourCast and NWS. Table F-1 and Table F-2 of Appendix F show the comparisons between recorded rainfall data by ScourCast and NWS in the National Weather Service Oklahoma City gauge, NWS COOP ID 346661 for 2007 and 2008 respectively.. The coordinates of the gauge were entered into GIS and precipitation data from ScourCast were extracted to those points and the values are also recorded in Appendix F. This gauge was not used in bias correction of the radar rainfall mosaic, and therefore represents an independent verification. The difference between the radar-based rainfall from ScourCast and the independent gauge was 6.4% for the two periods (2007-2008). The rainfall data used in this study can therefore considered accurate as they almost perfectly match with the independent NWS data.

4.2. Actual Evapotranspiration

Actual evapotranspiration validation for the current study uses Central Oklahoma Master Conservancy District (COMCD) data over Lake Thunderbird. The comparisons are shown in figure 12 below.

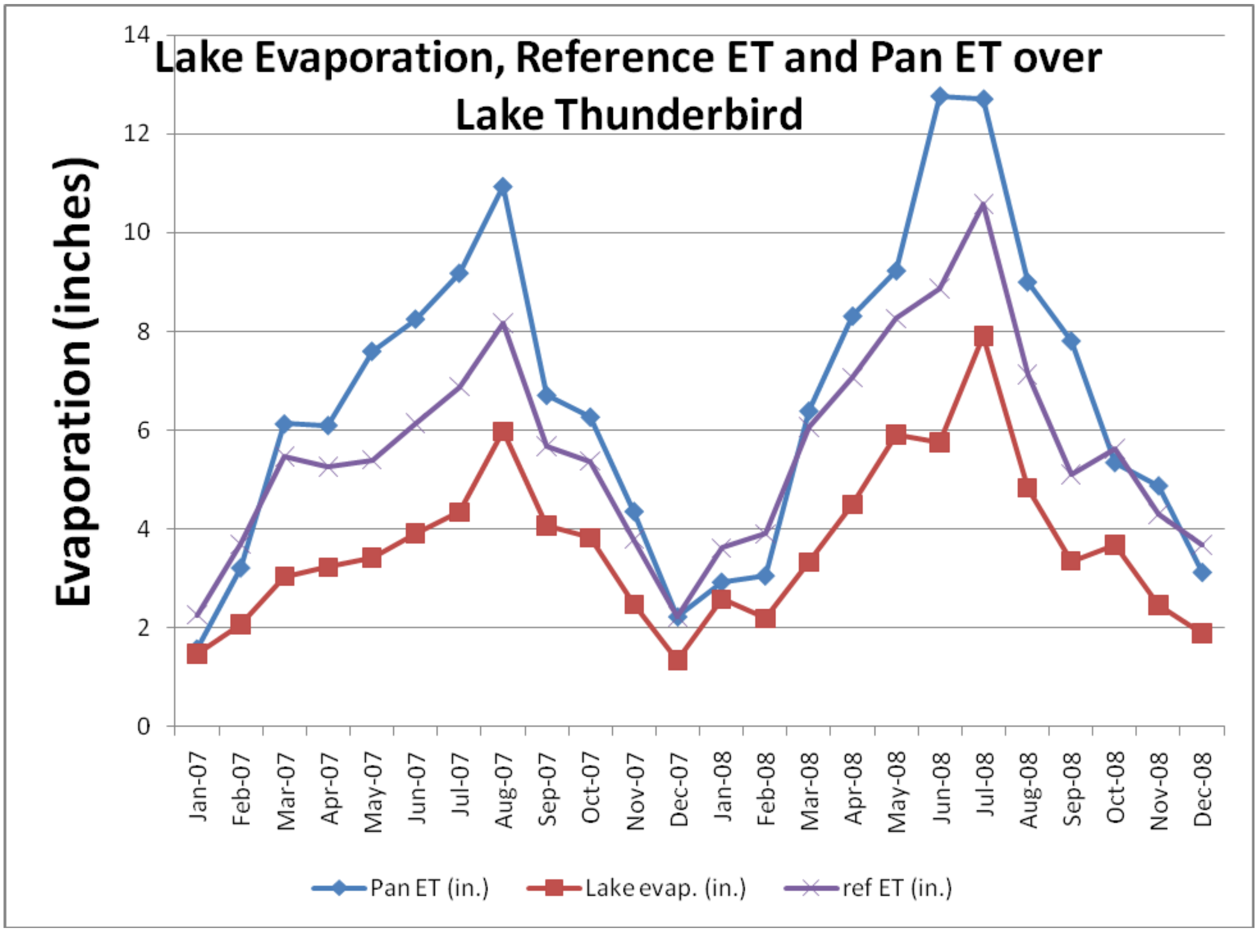

Figure 14: Lake Evaporation validation over Lake Thunderbird

To obtain lake evaporation, the estimates of aET according to the method described by Khan et al., 2009 was used. The average ratio of lake to pan evaporation for the two years of study is 0.59 for Lake Thunderbird. On cloudy days, lake evaporation may be underestimated, and the pan operated by COMCD is located a few miles from the lake. The average coefficient of reference ET taken from the Oklahoma Mesonet station in Cleveland County compared to the pan evaporation for the two study years is 0.92, which indicates that reference ET and pan ET are quite close, but biased by about 8%. The pan coefficient produced using satellite remote sensing of evaporation from the lake surface is close to pan coefficients published by Farnsworth et al. (1982). The closeness of the lake evaporation obtained by satellite methods compared to measured pan evaporation yields confidence in the M/M-ET method. In Table G-1 of Appendix G, the pan evaporation, reference ET, and lake evaporation are presented.

5. Analysis and Discussion

Natural Recourse Conservation Service (NRCS) in the National Engineering Handbook - Part 652 National Irrigation Guide and under Oklahoma Supplements estimate the supplemental water used for irrigation. The monthly consumptive use is described as the evapotranspiration and the net irrigation water use can be compared to aET – P. There is no detail concerning effective rain that was used by NRCS in computation of net irrigiation water requirement. Therefore, it is difficult to make direct comparisons between aET-P and the net irrigation water requirement. Consumptive water use, evaporation and transpiration is more directly related to aET – P. NRCS reports consumptive water use for Altus located near the Lugert-Altus Irrigation District, and in Goodwell located in Texas County. Although the data are given by city, the reported consumptive use is representative of irrigation water use in rural areas of the counties in which they are located. Table 6 presents the comparison between consumptive water use and aET – P.

Table 6: Estimated aET and annual consumptive water use in Texas County and in Lugert-Altus

Crops	Texas County			Lugert-Altus		
	aET 2007 (inches)	Annual Consumptive Use (Inches)	aET 2008 (inches)	aET 2007 (inches)	Annual Consumptive Use (Inches)	aET 2008 (inches)
Cotton	N/A	27.91	23.36	22.03	27.58	24.8
Winter Wheat	28.4	18.94	27.74	16.2	17.01	21.99
Corn	25.32	29.85	25.76	N/A	31.29	24.12
Sorghum	20.34	23.86	18.35	19.15	27.39	21.49

Table 7 below shows the differences observed between the net irrigation requirement by NRCS and the estimated values using the M/M-ET satellite estimation technique. Because 2007 and 2008 precipitation may not represent average conditions, clear comparison is not possible.

Table 7: Differences between net irrigation requirements by NRCS and estimated values of irrigation water use by satellite

	Crop	wheat	cotton	Corn	Sorghum
Texas County	**Net irrigation requirement in normal year (in)**	**6.31**	**18.7**	**17.85**	**13.55**
	Calculated water use in 2007 (inch)	14.79	N/A	11.47	11.42
	Calculated water use in 2008 (inch)	17.83	4.98	9.14	4.62
	Average of calculated water use (inch)	**16.31**	**4.98**	**10.305**	**8.02**
Lugert-Altus	**Net irrigation requirement in normal year (in)**	**3.83**	**14.62**	**17.85**	**15.83**
	Calculated water use in 2007 (inch)	5.19	8.43	N/A	7.25
	Calculated water use in 2008 (inch)	8.59	7.8		
	Average of calculated water use (inch)	**6.89**	**8.115**		

Other crops water requirements are given by USDA Economic Research Service (USDA/ERS, 2010) where it takes 20-22 inches to produce an optimal corn crop, 18-20 inches for a soybean crop, 12-13 inches for small grain, and 24-26 inches for alfalfa. Irrigation can reduce crop stress if rainfall does not provide this amount of moisture during the growing season. The Food and Agriculture Organization (FAO) also suggests crop water requirements, which are presented in Table 8 (FAO, 1986).

Table 8: Average crop water requirements and estimates from M/M-ET

Crop	FAO Water Requirement (in.)	M/M-ET Annual aET Texas County (in.)	M/M-ET Annual aET Lugert-Altus (in.)
Cotton	28-51	23.36	23.42
Corn	20-31	28.07	24.12
Sorghum	18-26	19.35	20.32
Winter Wheat	18-26	28.07	19.10

The values for crop water requirement given by FAO (Table 8 above) compared to the M/M-ET estimates of aET reveals that the satellite-based estimates are within the ranges suggested by FAO.

Based on the difference between aET and precipitation, it is estimated that 127,892 ac-ft in 2007 and 49,171 ac-ft in 2008 is used annually for irrigation of major crops in Texas County. In Lugert-Altus, 37,072 ac-ft was estimated for 2007 and 42,438 ac-ft in 2008. Considering the loss rate of about 36% (OWRB, 2001a), the volume of water used for irrigation in the Lugert-Altus Irrigation District would be 71,823*(1-0.36) or 45,967. Ac-ft which agrees closely with the water flux measured during the growing season as aET-P. Table 9 reports these volumes of estimated water use and reported data from OWRB.

Table 9: Annual irrigation water use and reported data from OWRB

	Texas County		Altus-Lugert	
	M/M-ET (acre-ft)	Irrigation Water Use OWRB (acre-ft)	M/M-ET (acre-ft)	Irrigation Water Use OWRB (acre-ft)
2007	127,892	226	37,072	45,967*
2008	49,171	174.5	42,438	-

*Includes adjustment for canal losses of 36%.

6. Conclusions

A satellite-based remote sensing technique was used to estimate crop water use in Texas County and the Altus-Lugert Irrigation District; water flux from the urban areas of Tulsa and Oklahoma City; and lake evaporation from Lake Thunderbird and Lake Texoma. Validation of these components of the water balance was accomplished by comparing water released from Lake Altus for the Lugert-Altus Irrigation District; published water use requirements for major crops, and by comparison of lake evaporation to pan evaporation. Precipitation was also used in the computation of crop water use, and was taken from radar-based rainfall mosaics, which were validated for the study period and found to be within 6.4%. Lake evaporation expressed as a fraction of pan evaporation was 0.59 and 0.65 for lakes Thunderbird and Texoma, respectively. Crop water use estimated by satellite remote sensing as aET-P was within 0.36% and in Texas County and within 12.89% for the Lugert-Altus compared to published values for the major crops grown.

Irrigation water use, of 127,892 ac-ft in 2007 and 49,171 ac-ft in 2008 in Texas County is under-reported in the OWRB data on permitted water use that is self reported through the OWRB permit requirements.

Whereas in Lugert-Altus, after accounting for canal losses, the volume released from the reservoir is quite close. The satellite-estimated irrigation water use was 37,072 ac-ft in 2007 and 42,438 ac-ft in 2008, which is within 19.4% and 7.7% during those years considering the same irrigation water use estimated by OWRB in 2007 and 2007. Water flux from the urban areas of Tulsa and Oklahoma City, was 29.53 inches, 32.34 inches, respectively in 2007. While in 2008, water flux transported to the atmosphere increased 34.75 inches and 40.94 inches, respectively. This water flux estimated from actual aET is less than potential, but follows closely reference ET. At least some of this aET is expected to derive from lawn irrigation, and other sources such as open water bodies that contribute to water flux transported to the atmosphere. Annual water flux (aET) measured by satellite did not exceed precipitation for Tulsa and Oklahoma City, and actual did not exceed potential ET except for two summer months in 2007 and 2008.

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Appendix A:

Table A-1: Growing season considered in Altus-Lugert Irrigation District

Crop	Growing season considered in Altus
Cotton	May-October
Winter Wheat	October - May
Corn	April-September
Sorghum	May-September

Table A-2: Growing season considered in Texas County

Crop	Growing season considered in Texas County
Cotton	June-October
Winter Wheat	September-June
Corn	May - September
Sorghum	June - October

Appendix B:

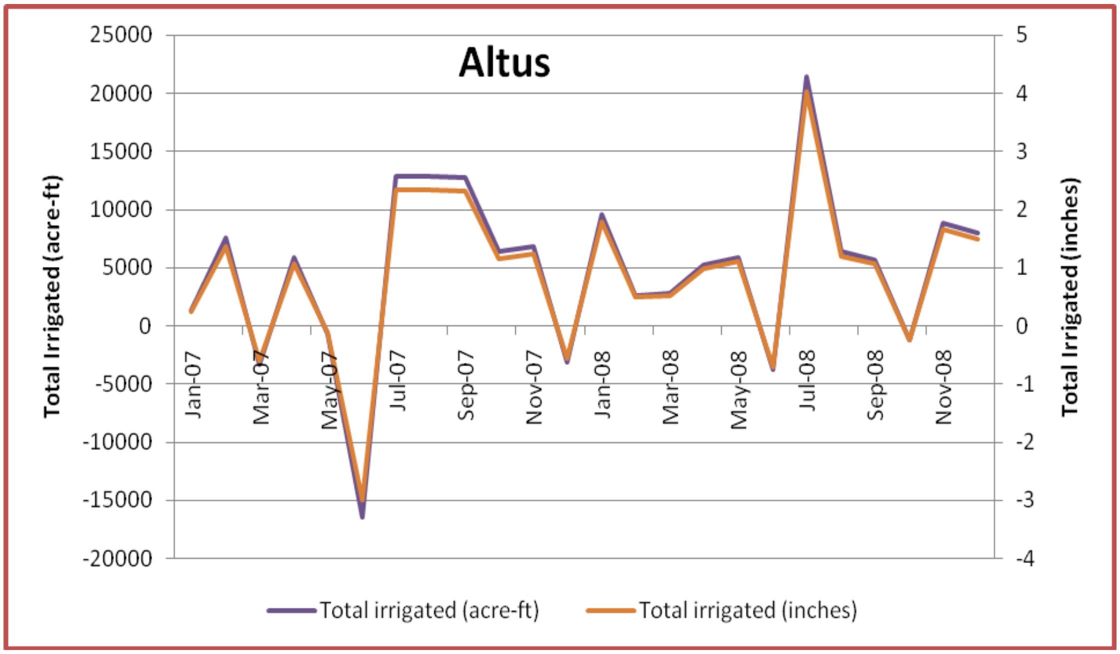

Figure B-13: aET-P variation in Altus for the study period

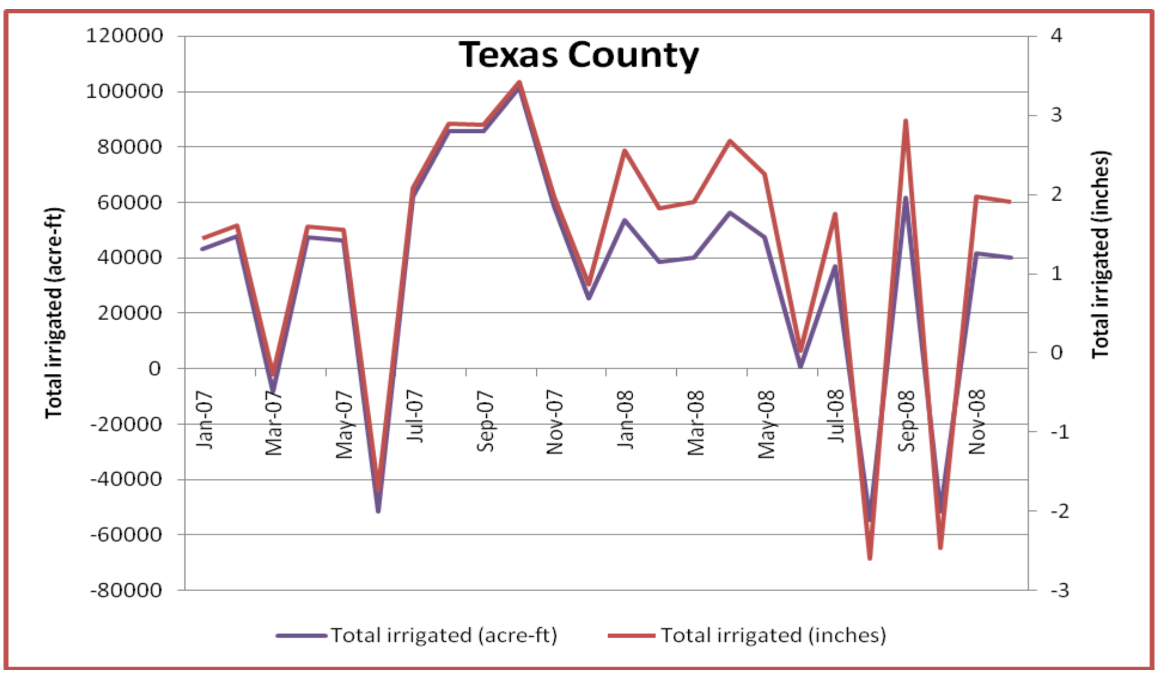

Figure B-14: aET-P variation in Texas County for the study period

Appendix C:

Table C-1: Water Fluxes in Oklahoma City in 2007

Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
Mean aET (in.)	1.40	1.65	2.3	2.47	2.73	3.23	3.70	4.09	3.44	3.33	2.03	1.16	32.34
Mean Precip. (in.)	1.59	0.59	6.43	2.64	8.27	11.43	6.07	5.25	2.62	3.53	0.99	2.31	51.72

Table C-2: Water Fluxes in Oklahoma City in 2008

Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Mean aET(in.)	2.70	1.84	3.01	3.87	4.92	4.85	5.97	3.84	2.66	3.08	2.32	1.88	40.94
Mean Precip. (in.)	0.46	2.71	4.23	3.63	4.58	6.29	1.56	8.50	1.20	1.42	1.19	0.74	36.52

Table C-3: Actual ET, reference ET and precipitation in Oklahoma City

Date	mean aet	mean ref	bias aet and ref et	Precip(inches)
Jan-07	1.40	2.27	38.16	1.59
Feb-07	1.65	3.63	54.62	0.59
Mar-07	2.30	5.44	57.74	6.43
Apr-07	2.47	5.26	53.13	2.64
May-07	2.73	5.54	50.62	8.27
Jun-07	3.23	6.27	48.44	11.43
Jul-07	3.70	7.13	48.13	6.07
Aug-07	4.90	8.71	43.70	5.25
Sep-07	3.44	6.02	42.96	2.62
Oct-07	3.33	5.64	40.97	3.53
Nov-07	2.03	3.85	47.15	0.99
Dec-07	1.16	2.17	46.78	2.31
Jan-08	2.70	3.82	29.46	0.46
Feb-08	1.84	3.92	52.90	2.71
Mar-08	3.01	6.01	49.92	4.23
Apr-08	3.87	7.27	46.77	3.63
May-08	4.92	8.64	43.07	4.58
Jun-08	4.85	9.38	48.33	6.29
Jul-08	5.97	10.77	44.54	1.56
Aug-08	3.84	7.41	48.14	8.50
Sep-08	2.66	5.30	49.86	1.20
Oct-08	3.08	5.78	46.74	1.42
Nov-08	2.32	4.42	47.50	1.19
Dec-08	1.88	3.83	50.89	0.74
Average bias aet and ref et (%)			**47.15**	

Appendix D:

Table D-1: Water Fluxes in Tulsa in 2007

Date	Jan	Feb	Mar	Apr	May	Jun	Jul-	Aug	Sep	Oct	Nov	Dec	Total
Mean aET (in.)	1.39	1.61	2.54	2.41	2.41	3.11	3.37	4.11	2.82	2.81	1.99	0.97	29.53
Mean Precip (in.)	1.91	0.84	3.50	2.66	8.86	10.11	3.34	1.39	5.95	3.32	0.16	2.61	44.65

Table D-2: Water Fluxes Tulsa in 2008

Date	Jan	Feb	Mar	Apr	May	Jun	Jul-	Aug	Sep	Oct	Nov	Dec	Total
Mean aET (in.)	2.02	1.73	2.66	3.47	4.20	3.97	5.05	3.11	2.19	2.49	2.03	1.82	34.75
Mean Precip (in.)	0.49	1.86	5.04	6.98	9.62	10.10	4.95	2.54	3.29	2.21	1.34	1.68	50.08

Table D-3: Actual ET, reference ET and precipitation over Tulsa area

Date	Mean aET (in.)	Mean Ref ET (in.)	Bias of aET and ref ET (%)	Precipitation(in.)
Jan-07	1.39	2.08	33.40	1.91
Feb-07	1.61	3.43	53.19	0.84
Mar-07	2.54	5.44	53.30	3.50
Apr-07	2.41	5.41	55.43	2.66
May-07	2.41	5.34	54.80	8.86
Jun-07	3.11	5.91	47.47	10.11
Jul-07	3.37	6.59	48.91	3.34
Aug-07	4.11	7.68	46.45	1.39
Sep-07	2.82	4.97	43.26	5.95
Oct-07	2.81	4.72	40.41	3.32
Nov-07	1.99	3.49	42.99	0.16
Dec-07	0.97	1.83	47.19	2.61
Jan-08	2.02	2.88	29.96	0.49
Feb-08	1.73	3.10	44.30	1.86
Mar-08	2.66	5.29	49.73	5.04
Apr-08	3.47	6.32	45.07	6.98
May-08	4.20	7.11	40.87	9.62
Jun-08	3.97	7.34	45.99	10.10
Jul-08	5.05	8.68	41.85	4.95
Aug-08	3.11	5.99	48.09	2.54
Sep-08	2.19	4.28	48.80	3.29
Oct-08	2.49	4.50	44.60	2.21
Nov-08	2.03	3.63	43.92	1.34
Dec-08	1.82	3.00	39.31	1.68
Average	**Bias of aET and ref ET (%)**		**46.08**	

Appendix E:

TableE-1: Lake Texoma variation of evaporation, and reference ET

Date	Reference ET (in.)	Lake evaporation(in.)	Bias (%)	aET/ref ET
Jan-07	2.21	1.22	44.89	0.55
Feb-07	3.94	2.36	40.11	0.6
Mar-07	5.06	3.23	36.24	0.64
Apr-07	5.1	3.57	30.06	0.7
May-07	5.34	3.59	32.78	0.67
Jun-07	6.14	3.88	36.85	0.63
Jul-07	6.29	4.19	33.37	0.67
Aug-07	7.43	5.88	20.89	0.79
Sep-07	5.88	4.08	30.49	0.7
Oct-07	5.41	3.64	32.68	0.67
Nov-07	3.96	2.38	40.08	0.6
Dec-07	2.63	1.39	47.16	0.53
Jan-08	3.22	1.92	40.53	0.59
Feb-08	4.24	2.77	34.73	0.65
Mar-08	6.02	4.21	30.18	0.7
Apr-08	6.7	4.77	28.79	0.71
May-08	7.49	5.77	22.98	0.77
Jun-08	9.22	6.02	34.74	0.65
Jul-08	10.31	7.75	24.89	0.75
Aug-08	7.2	5.13	28.7	0.71
Sep-08	5.29	3.43	35.15	0.65
Oct-08	5.64	3.47	38.4	0.62
Nov-08	4.17	2.34	44.01	0.56
Dec-08	3.48	1.97	43.29	0.57
Average			34.67	0.65

Appendix F:

Station Name: Oklahoma City Will Rogers Airport

Type: LAND SURFACE COOP AB ASOS ASOS-NWS

Call Sign/ICS: OKC / KOKC

WBAN: 13967

COOP ID: 346661

Climate Division: OK-05 - Central

WMO ID: 72353

In Service: 02 Apr 1932 to Present

Elevation: 391.7m (1285') above s/l

Lat/Lon: 35°23'N / 97°36'W

County: Oklahoma

Table F-1: Comparison of recorded precipitation,

Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ScourCast	1.19	0.54	7.92	2.61	9.09	10.55	6.06	5.16	4.20	3.72	0.92	2.28
NWS	2.08	0.62	8.02	2.57	8.49	10.06	6.31	5.39	5.73	3.72	0.53	3.43
bias (%)	-42.89	-13.31	-1.30	1.68	7.04	4.91	-3.99	-4.27	-26.73	-0.12	73.48	-33.66

Table F-2: Comparison of recorded precipitation, 2008

Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ScourCast	0.66	3.29	4.54	3.82	4.37	7.10	1.60	11.01	0.93	1.34	0.73	0.65
NWS	0.65	2.88	3.29	4.17	4.54	5.83	1.07	9.95	0.59	1.63	0.70	0.52
bias (%)	1.46	14.31	38.06	-8.30	-3.69	21.71	49.76	10.64	57.05	-17.68	4.23	25.14

Appendix G:

Table G-1: Validation of lake evaporation over Lake Thunderbird

Date	Pan ET (in.)	Lake evap (in.)	Reference ET (in.)	Lake evap./pan	ref/pan	Lake evap/ref
Jan-07	1.58	1.48	2.26	0.93	1.43	0.65
Feb-07	3.22	2.07	3.69	0.64	1.15	0.56
Mar-07	6.13	3.04	5.46	0.50	0.89	0.56
Apr-07	6.10	3.23	5.26	0.53	0.86	0.61
May-07	7.60	3.42	5.40	0.45	0.71	0.63
Jun-07	8.25	3.91	6.14	0.47	0.74	0.64
Jul-07	9.18	4.34	6.88	0.47	0.75	0.63
Aug-07	10.93	5.97	8.17	0.55	0.75	0.73
Sep-07	6.71	4.07	5.68	0.61	0.85	0.72
Oct-07	6.27	3.82	5.38	0.61	0.86	0.71
Nov-07	4.36	2.47	3.79	0.57	0.87	0.65
Dec-07	2.23	1.34	2.23	0.60	1.00	0.60
Jan-08	2.93	2.58	3.62	0.88	1.23	0.71
Feb-08	3.06	2.19	3.90	0.72	1.28	0.56
Mar-08	6.39	3.33	6.06	0.52	0.95	0.55
Apr-08	8.31	4.50	7.06	0.54	0.85	0.64
May-08	9.23	5.90	8.26	0.64	0.90	0.71
Jun-08	12.76	5.76	8.87	0.45	0.69	0.65
Jul-08	12.70	7.90	10.58	0.62	0.83	0.75
Aug-08	9.00	4.83	7.13	0.54	0.79	0.68
Sep-08	7.81	3.35	5.11	0.43	0.65	0.66
Oct-08	5.35	3.68	5.62	0.69	1.05	0.65
Nov-08	4.88	2.45	4.31	0.50	0.88	0.57
Dec-08	3.13	1.89	3.68	0.60	1.18	0.51
Average				0.59	0.92	0.64

Appendix H:

Table H-1:

Crops	Average Estimated Annual ET in Texas County (inches)	Annual Consumptive Use in Texas County (Inches)	Difference (%)	Average Estimated Annual ET in Texas County (inches) in Lugert Altus	Annual Consumptive Use in Lugert-Altus (inches)	Difference (%)
Cotton	23.36	27.91	16.30	23.415	27.58	15.10
Winter Wheat	28.07	18.94	-48.20	19.095	17.01	-12.25
Corn	25.54	29.85	14.44	24.12	31.29	22.91
Sorghum	19.345	23.86	18.92	20.32	27.39	25.817
Average			0.36			12.89