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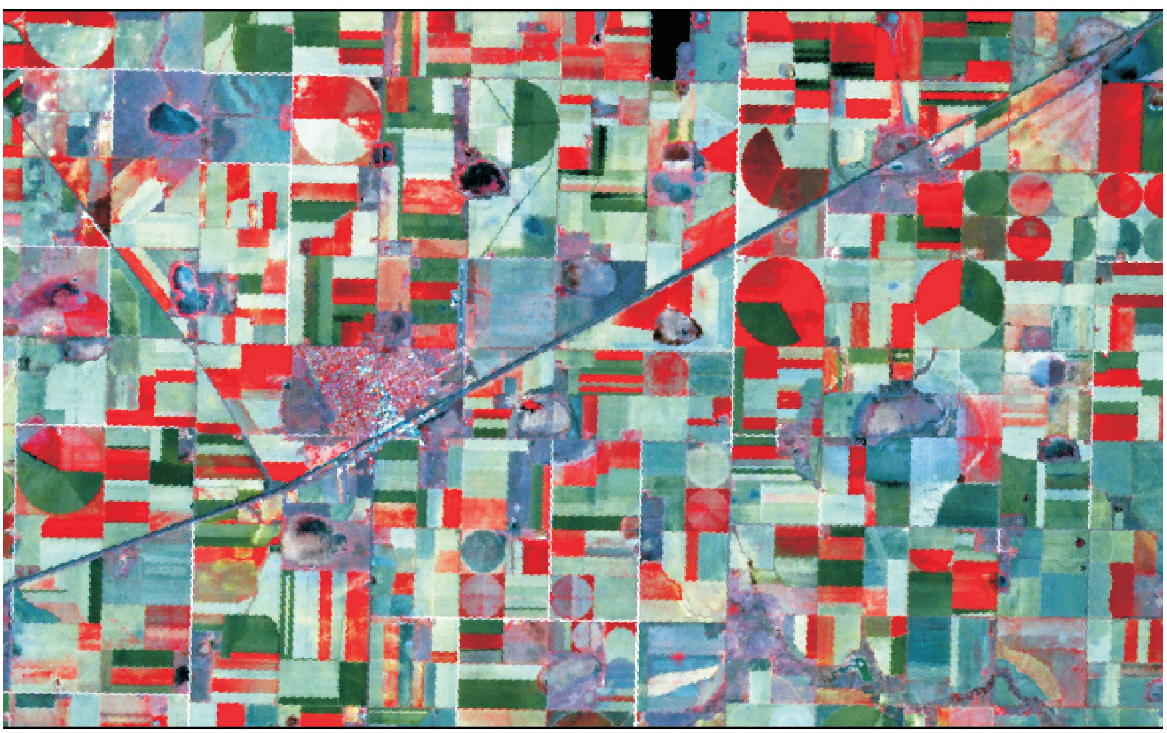
Comparison of Irrigation Water Use Estimates Calculated From Remotely Sensed Irrigated Acres and State Reported Irrigated Acres in the Lake Altus Drainage Basin, Oklahoma and Texas, 2000 Growing Season

Water-Resources Investigations Report 03-4155



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Comparison of Irrigation Water Use Estimates Calculated From Remotely Sensed Irrigated Acres and State Reported Irrigated Acres in the Lake Altus Drainage Basin, Oklahoma and Texas, 2000 Growing Season

By Jason R. Masoner[1], Carol S. Mladinich[2], Alexandria M. Konduris[2], and S. Jerrod Smith[1]

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Conversion Factors and Datum

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	0.003785	cubic meter (m^3)
acre-foot (acre-ft)	43,560	cubic feet (ft^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
cubic foot (ft^3)	7.48	gallon (gal)
million gallons per day (Mgal/d)	0.003785	cubic meter per day (m^3/d)
	Watts	
langleys per day (lang/day)	1,004,140.8	watts per meter squared (watts/m^2)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is North American Datum of 1983 (NAD 83).

Comparison of Irrigation Water Use Estimates Calculated From Remotely Sensed Irrigated Acres and State Reported Irrigated Acres in the Lake Altus Drainage Basin, Oklahoma and Texas, 2000 Growing Season

By Jason R. Masoner, Carol S. Mladinich, Alexandria M. Konduris, and S. Jerrod Smith

Abstract

Increased demand for water in the Lake Altus drainage basin requires more accurate estimates of water use for irrigation. The U.S. Geological Survey, in cooperation with the U.S. Bureau of Reclamation, is investigating new techniques to improve water-use estimates for irrigation purposes in the Lake Altus drainage basin. Empirical estimates of reference evapotranspiration, crop evapotranspiration, and crop irrigation water requirements for nine major crops were calculated from September 1999 to October 2000 using a solar radiation-based evapotranspiration model. Estimates of irrigation water use were calculated using remotely sensed irrigated crop acres derived from Landsat 7 Enhanced Thematic Mapper Plus imagery and were compared with irrigation water-use estimates calculated from irrigated crop acres reported by the Oklahoma Water Resources Board and the Texas Water Development Board for the 2000 growing season. The techniques presented will help manage water resources in the Lake Altus drainage basin and may be transferable to other areas with similar water management needs.

Irrigation water use calculated from the remotely sensed irrigated acres was estimated at 154,920 acre-feet; whereas, irrigation water use calculated from state reported irrigated crop acres was 196,026 acre-feet, a 23 percent difference. The greatest difference in irrigation water use was in Carson County, Texas. Irrigation water use for Carson County, Texas, calculated from the remotely sensed irrigated acres was 58,555 acre-feet; whereas, irrigation water use calculated from state reported irrigated acres was 138,180 acre-feet, an 81 percent difference. The second greatest difference in irrigation water use occurred in Beckham County, Oklahoma. Differences between the two irrigation water use estimates are due to the differences of irrigated crop acres derived from the mapping process and those reported by the Oklahoma Water Resources Board and Texas Water Development Board.

Introduction

Increased demand for water in the Lake Altus drainage basin requires more accurate estimates of water use for irrigation. Agriculture is the primary land use in the drainage basin. Ninety-one percent of water use in the drainage basin in 1995 was for irrigation purposes (R.L. Tortorelli, USGS, written commun., 2001). Lake Altus supplies water to the Lugert-Altus Irrigation District using a 270-mile system of canals downstream from the dam (Oklahoma Water Resources Board, 2000). Lake Altus was built by the Bureau of Reclamation from 1941 to 1948 for flood control, water supply for the City of Altus, and irrigation of about 46,000 acres (A. Ensley, Lugert-Altus Irrigation District, oral commun., 2002). The Lugert-Altus Irrigation District annually supplies more than 85,000 acre-feet of water for agricultural purposes (Oklahoma Water Resources Board, 2000).

The U.S. Geological Survey, in cooperation with the U.S. Bureau of Reclamation, investigated new techniques to improve water-use estimates for irrigation purposes in the Lake Altus drainage basin (fig. 1). Empirical estimates of reference evapotranspiration, crop evapotranspiration, and crop irrigation water requirements for alfalfa, corn, cotton, hay, peanuts, sorghum, soybeans, sunflowers, and wheat were calculated on a monthly and seasonal basis from September 1999 to October 2000 using an evapotranspiration model by Doorenbos and Pruitt (1977). The model is commonly referred to as the radiation method and is accurate in arid and sub-humid areas and less accurate near the ocean in cooler climates (U.S. Department of Agriculture, 1993). These empirical estimates of irrigation water use were used with estimated irrigated acres to calculate irrigation water use in the Lake Altus drainage basin in Oklahoma and Texas.

Purpose and Scope

The purpose of this report is to present the techniques and results of an effort to map irrigated crop acres in the Lake Altus drainage basin using satellite imagery and remote sensing tech-

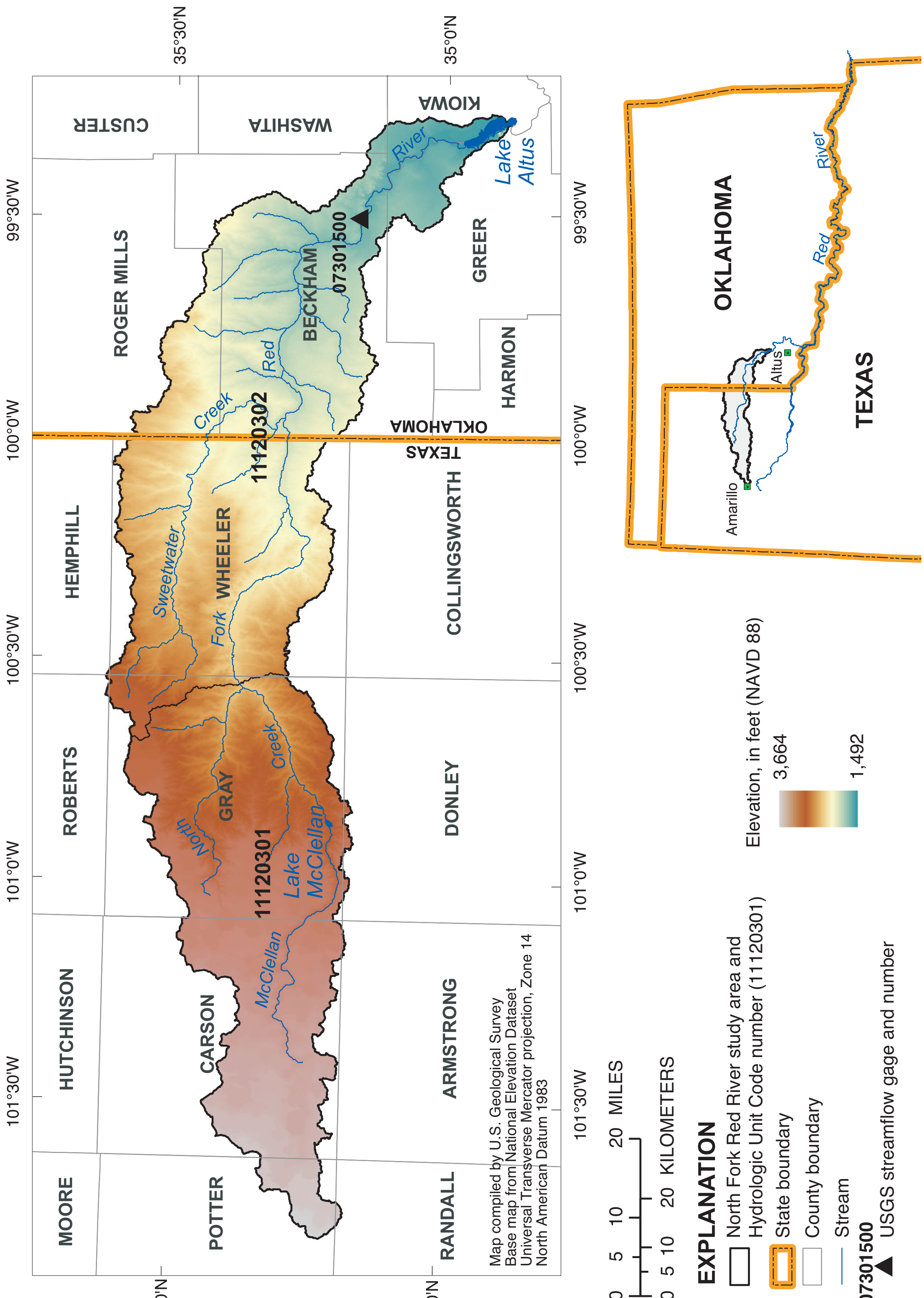

Figure 1. Map of the Lake Altus drainage basin.

niques, and compare irrigation water use estimates calculated from the remotely sensed irrigated acres with those calculated from state reported irrigated crop acres for the 2000 growing season. This report presents: (1) mapping of land use and irrigated crop acres from multiple dates of Landsat 7 Enhanced Thematic Mapper Plus (ETM+) imagery; (2) reported irrigated crop acres from Oklahoma Water Resources Board (OWRB) and Texas Water Development Board (TWDB); (3) seasonal estimates of reference evapotranspiration, crop evapotranspiration, and crop irrigation water requirements; (4) seasonal estimates of irrigation water use for alfalfa, corn, cotton, hay, peanuts, sorghum, soybeans, sunflowers, and wheat; and (5) a comparison of irrigation water use estimates calculated from remotely sensed irrigated acres and irrigation water use estimates calculated from the state reported irrigated acres.

Seasonal irrigation water use, referred to in this report as irrigation water use during the 2000 growing season, was calculated for each crop on a countywide basis for major crops by multiplying seasonal irrigation requirements by the number of irrigated crop acres in each county. Irrigation water use was calculated using two sources of irrigated crop acres: (1) irrigated crop acres derived from remote sensing techniques and Landsat 7 ETM+ imagery, referred to as remotely sensed irrigated acres; and (2) irrigated acres reported by the OWRB and the TWDB, referred to as state reported irrigated acres. Irrigation water use estimates calculated from remotely sensed irrigated crop acres were compared with irrigation water use estimates calculated from state reported irrigated acres for the 2000 growing season.

Estimates of water use for irrigation provided in this report will facilitate better management of water resources in the Lake Altus drainage basin. Methodologies described in this report to calculate estimates of reference evapotranspiration, crop evapotranspiration, crop irrigation water requirements, and irrigation water use, may be transferable to other areas that may have similar water management needs. The irrigation water requirements presented in this report can be used with estimates of irrigated acres from anywhere in the drainage basin to calculate irrigation water use.

Description of Study Area

The study area consists of the Lake Altus drainage basin (fig.1). Lake Altus is located on the border of Greer and Kiowa Counties in southwestern Oklahoma, approximately 20 miles north of the town of Altus. The drainage area for Lake Altus is approximately 2,515 square miles, 399 square miles of which are non-contributing (Blazs and others, 2001). Most of the drainage basin, includes parts of Beckham, Carson, Gray, and Wheeler Counties (table 1).

The North Fork Red River is the major source of surface-water inflow for Lake Altus. The North Fork Red River is one of five major tributaries of the Red River. U.S. Geological Survey streamflow-monitoring station 07301500, North Fork Red River Near Carter, Oklahoma, recorded a mean annual flow of 93,230 acre-feet from 1945 through 2000 (Blazs and others, 2001). Average annual precipitation in the study area ranges from about 18 inches in the west at the headwaters to 26 inches near Lake Altus in the east (Daly and others, 1994).

Agriculture is the major land use and is mainly supported by water from the High Plains Aquifer, also referred to as the Ogallala Aquifer, and alluvial and terrace deposits along the North Fork Red River.

The High Plains Aquifer is an unconsolidated and semi-consolidated aquifer of Tertiary age and associated alluvial and terrace deposits are of Quaternary age (Havens and others, 1985, p. 348). The High Plains Aquifer consists mostly of fine sand and silts with lesser quantities of clay, gravel, and minor beds of limestone and caliche (Hart and others, 1976). Well yields range from 100 to 1,000 gallons per minute; with some yields exceeding 1,500 gallons per minute (Havens and others, 1985, p. 347).

The North Fork Red River alluvial and Beckham and Tillman terrace deposits consist of silt, clay, and gravel grading downward into fine to coarse sand (Havens and others, 1985, p. 348). Well yields range from 100 – 200 gallons per minute in the alluvium and 200 – 500 gallons per minute in the Beckham and Tillman terrace (Havens and others, 1985, p. 348).

The length of growing season for crops is closely related to temperature and has a substantial effect on the amount of water used by crops. There are two primary growing seasons in the Lake Altus drainage basin. Winter wheat is grown in the first growing season, which occurs from early October through early May (peak greenness), with harvesting in early June (McDaniels, 1960, and U.S. Department of Agriculture, 1998). Corn, cotton, peanuts, sorghum, soybeans, and sunflowers are grown in the second growing season, which occurs from mid-March through late July to mid-August (peak greenness) with harvesting in September or November (McDaniels, 1960, and U.S. Department of Agriculture, 1998).

Previous Study

Heimes and Luckey (1982) describe a method for estimating historical irrigation water requirements for the High Plains Aquifer from 1949 though 1978. There were two primary components used to estimate irrigation water use; irrigated crop acres and crop irrigation requirements. The report by Heimes and Luckey (1982) acquired estimates of irrigated acres by county from the Census of Agriculture (U.S. Department of Commerce, 1949 to 1978). A modified version of the Blaney-Criddle formula was used to estimate irrigation water requirements for major crops growing above the High Plains Aquifer (U.S. Department of Agriculture, 1970). The Modified Blaney-Criddle differs from the original Blaney-Criddle in that two adjustment factors are used to better estimate crop evapotranspiration. A climate coefficient correlates monthly crop evapotranspiration with the mean monthly temperature, and a growth-stage coefficient tracks crop growth development throughout the growing cycle. The Modified Blaney-Criddle method is

Table 1. Portions of counties in Oklahoma and Texas in the Lake Altus drainage basin

Counties	State	Portion of county in drainage basin (acres)	Portion of county in drainage basin (percent)
Beckham	Okla.	365,310	20.4
Greer	Okla.	47,686	2.7
Kiowa	Okla.	32,384	1.8
Roger Mills	Okla.	94,737	5.2
Washita	Okla.	2,551	0.1
Carson	Tex.	264,860	14.7
Donley	Tex.	7,101	0.4
Gray	Tex.	471,616	26.3
Randall	Tex.	1,227	0.1
Potter	Tex.	40,104	2.2
Wheeler	Tex.	467,473	26.1

widely used because of the limited climate information needed to calculate crop evapotranspiration and has been widely used historically by federal and state agriculture programs. There are more accurate methods that use solar radiation, wind speed, temperature, and humidity data to estimate crop evapotranspiration (U.S. Department of Agriculture, 1970).

Historical Freshwater Withdrawals

Freshwater withdrawal estimates for 1995 were obtained for 8-digit Hydrologic Unit Code (HUC) 11120301 and 11120302 (fig. 1) from the U.S. Geological Survey (R.L. Tortorelli, USGS, written commun., 2001). Total consumptive use from the Lake Altus drainage basin was estimated to be 120,983 acre-feet or 108.15 million gallons per day. Consumptive use for irrigation was estimated to be 109,781 acre-feet or 98.24 million gallons per day (table 2). Ground water supplies about 69 percent of total self-supplied water withdraws in the drainage basin; whereas, surface water accounts for the remaining 31 percent. The western half (11120301) of the study area accounted for 61 percent of the total self-supplied withdrawals in the drainage basin because of greater withdrawals from the High Plains Aquifer for irrigation. Withdrawals in the western half (11120301) are predominantly supplied by ground water (94 percent); whereas, withdrawals in the eastern half (11120302) are predominantly supplied by surface water (72 percent) (table 2).

Irrigation accounts for 82 percent of total self-supplied water withdrawals in the drainage basin. However, the majority of surface-water withdrawals and irrigated acres in the eastern half are utilized downstream in the Altus-Lugert Irrigation District. The distribution of other less prevalent self-supplied withdrawals included 4.9 percent for public use, 4.5 percent for livestock use, 4.4 percent for industrial use, 3.6 percent for mining use, and 0.4 percent for domestic use (calculated from table 2). Detailed explanations of water use terms used in this section can be acquired at URL http://ok.water.usgs.gov/wateruse/definitions.html

Acknowledgments

The authors wish to express their appreciation to personnel from U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS) and Farm Service Agency (FSA) offices for providing field maps of croplands and information about agricultural practices that were used to calibrate remote sensing data when determining irrigated croplands. Howard Johnson, Oklahoma Climatological Survey (OCS) and Cleon Napkin, NRCS, provided climate data used in this report. Jerry Walker and Tom Spofford, NRCS, provided technical advice about the evapotranspiration model used for this report. Michael Sughru, U.S. Geological Survey made several suggestions to improve the remote sensing part of this report.

Table 2. 1995 estimated freshwater withdrawals for cataloging units 11120301 and 11120302 (data source, R.L. Tortorelli, U.S. Geological Survey, written commun., 2001)

[data units in million gallons per day (mgd) unless noted; gal/day, gallon per day]

Public supply category	1120301	1120302	Total basin	Commercial category	1120301	1120302	Total basin
Population served by ground water, in thousands	7.64	20.21	27.85	Total self-supplied withdrawals, ground water	0.07	0.25	0.32
Population served by surface water, in thousands	4.64	0.00	4.64	Total self-supplied withdrawals, surface water	0.00	0.00	0.00
Total population served, in thousands	12.28	20.21	32.49	Total self-supplied withdrawals	0.07	0.25	0.32
Total self-supplied withdrawals, ground water	1.25	4.74	5.99	Consumptive use, total	0.04	0.10	0.14
Total self-supplied withdrawals, surface water	0.00	0.00	0.00				
Total self-supplied withdrawals, total	1.25	4.74	5.99				
Per-capita use, in gal/d	101.79	234.53	184.36				

Domestic category	1120301	1120302	Total basin	Industrial category	1120301	1120302	Total basin
Self-supplied population, in thousands	1.20	1.85	3.05	Total self-supplied withdrawals, ground water	5.19	0.20	5.39
Total self-supplied withdrawals, ground water	0.26	0.21	0.47	Total self-supplied withdrawals, surface water	0.00	0.00	0.00
Total self-supplied withdrawals, surface water	0.00	0.00	0.00	Total self-supplied withdrawals	5.19	0.20	5.39
Total self-supplied withdrawals	0.26	0.21	0.47	Consumptive use, total	0.34	0.04	0.38
Per-capita use, self-supplied, in gal/d	216.67	113.51	154.10				
Per-capita use, public-supplied, in gal/d	194.63	95.99	133.27				
Consumptive use, total	1.06	0.73	1.79				

Mining category	1120301	1120302	Total basin	Total livestock category	1120301	1120302	Total basin
Total self-supplied withdrawals, ground water	3.65	0.73	4.38	Total self-supplied withdrawals, ground water	0.66	0.63	1.29
Total self-supplied withdrawals, surface water	0.00	0.00	0.00	Total self-supplied withdrawals, surface water	1.84	2.25	4.09

Table 2. 1995 estimated freshwater withdrawals for cataloging units 11120301 and 11120302 (data source, R.L. Tortorelli, U.S. Geological Survey, written commun., 2001)—Continued.

[data units in million gallons per day (mgd) unless noted; gal/day, gallon per day]

Mining category—Continued	1120301	1120302	Total basin
Total self-supplied withdrawals	3.65	0.73	4.38
Consumptive use, total	2.12	0.10	2.22

Total livestock category—Continued	1120301	1120302	Total basin
Total self-supplied withdrawals	2.50	2.88	5.38
Consumptive use, total	2.50	2.88	5.38

Irrigation category	1120301	1120302	Total basin
Total self-supplied withdrawals, ground water	59.09	6.80	65.89
Total self-supplied withdrawals, surface water	2.41	31.80	34.21
Total self-supplied withdrawals	61.50	38.60	100.10
Consumptive use, total	61.50	36.74	98.24
Conveyance loss	0.00	1.59	1.59
Thousand acres irrigated, sprinkler	22.10	11.35	33.45
Thousand acres irrigated, microirrigation	0.01	0.13	0.14
Thousand acres irrigated, surface water	38.06	38.73	76.79
Thousand acres irrigated	60.17	50.21	110.38
Reclaimed wastewater	2.69	0.08	2.77

Reservoir evaporation category	1120301	1120302	Total basin
Reservoir surface area, in thousand acres	0.32	4.74	5.06
Reservoir evaporation, in thousand acre-feet per year	1.59	23.16	24.75

Totals, overall category	1120301	1120302	Total basin
Total self-supplied withdrawals, ground water	70.17	13.56	83.73
Total self-supplied withdrawals, surface-water	4.25	34.05	38.30
Total self-supplied withdrawals	74.42	47.61	122.03
Total consumptive use	67.56	40.59	108.15
Total conveyance losses	0.00	1.59	1.59

Determination of land use and irrigated crop acres by remote sensing

Enhanced Thematic Mapper Plus (ETM+) (U. S. Geological Survey, 2002a) imagery was used to map land use and irrigated croplands during the 2000 growing season. Land use was mapped using a supervised clustering algorithm based on statistical signatures for 25 pixel classes (table 3). Ancillary information from the National Land Cover Dataset 1992 (NLCD) (U.S. Geological Survey, 2002b) and ground reference crop data from the FSA county offices were used to aid in the development of spectral signatures used to classify pixel classes. The NLCD is categorized into broad land-cover types and identifies three classes of agriculture: row crops, small grains, and hay/pasture. These classes were used as an ancillary data source to aid in the crop delineation.

Irrigated crop acres were determined using a ratio vegetation index consisting of a near infrared band (band 4) divided by a visible red band (band 3) ratio to create the vegetation index (Qi and others, 2002). The near infrared band and visible red band ratio enhances certain features such as greenness of vegetation not generally visible. The resulting images consisted of a single gray-scale band with bright white pixels representing irrigated crop acres (fig. 2). Non-irrigated vegetation was displayed as ranges of gray. A threshold value was selected at which everything greater than that value was considered to be irrigated; everything less than that value was considered to be non-irrigated. Threshold values were selected for each Landsat scene based on the radiometric balancing applied to each Landsat scene. Some editing was required to remove riparian areas or to add known irrigated agriculture that was less than the threshold value. Appendices 1 through 10 provide county-specific information on the number of pixels and number of acres for 25 land use classes in parts of each county in the drainage basin determined from the mapping process. A null pixel class is listed in the appendices and represents the part of a county that is outside the portion of the drainage basin in the county.

Identification of crop types with Landsat 7 ETM+ satellite imagery is a routine application of remote sensing technology. Image date selection is vital for successful identification of many vegetation covers, especially agricultural crops (Rundquist and others, 2002). Identification of agricultural crops using satellite imagery requires knowledge of crop phenology, climate for the particular growing season, and ground reference information about specific agricultural practices in the drainage basin. The best date range to identify winter wheat is between late March through early May, when wheat is at peak greenness. To identify corn and other summer crops, the best date range is late July to mid-August.

The original study plan was to use the same imagery used in the generation of the NLCD and in the High Plains Aquifer study (Qi and others, 2002) because two dates were used, a winter leaf-off date and a summer leaf-on date. However, these dates were less than optimal for crop delineation. The dates for the selected imagery used for this report were selected to occur

Table 3. Categories of pixel classes used to define land use and irrigated crop acres in the Lake Altus drainage basin during the 2000 growing season

Croplands	General land use	Irrigated croplands
Alfalfa	Fallow	Alfalfa
Corn	Grasslands	Corn
Cotton	Trees	Peanut
Cowpeas	Urban	Sorghum
Hay/Pasture	Water	Soybeans
Oats	Unknown crops	Wheat
Peanut	Unknown irrigated	
Rye		
Sorghum		
Soybeans		
Sunflowers		
Wheat		

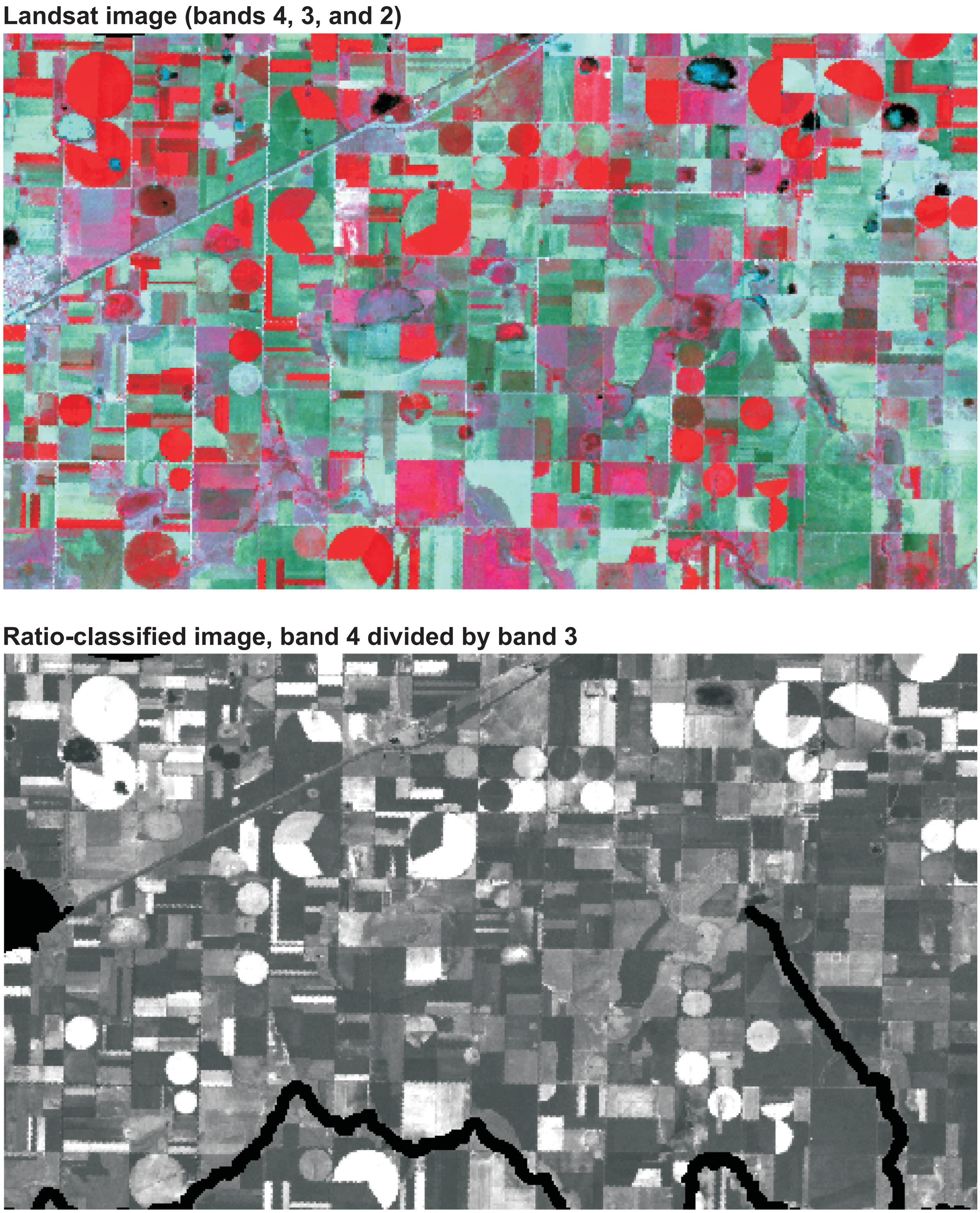

Figure 2. An example of a ratio-classified image. The brightness of pixels represents values for the ratio of band 4 to band 3. The brighter the pixel, the higher the ratio and the healthier and greener the vegetation.

Figure 3. Locations and names of Landsat scenes used to acquire Landsat 7 Enhanced Thematic Mapper Plus imagery.

during peak greenness periods for both winter wheat and summer crops. The Lake Altus drainage basin spans four Landsat scenes used to acquire ETM+ images, Path/Row 30/35,36 and Path/Row 29/35,36 (fig. 3). Two dates were originally selected for analysis. A spring date (Path/Row 30/35,36 – 5/20/2000, Path/Row 29/35,36 – 5/13/2000) to map the winter wheat and a summer date (Path/Row 30/35,36 – 7/23/2000, Path/Row 29/35,36 – 8/1/2000) to map the remainder of the crops in the basin. Imagery from a third date (Path/Row 30/35,36 – 4/18/2000, Path/Row 29/35,36 – 3/26/2000) was analyzed because the winter wheat green-up was earlier in the season, which caused harvesting to occur earlier than normal in Texas counties. The 2000 growing season was selected because it was extremely dry all season in the Texas counties and dry in the fall, winter, and late summer in the Oklahoma counties. Therefore, more irrigation was required than in a normal growing season, thus enabling better delineation between irrigated crops and non-irrigated cropland and rangeland.

Preprocessing

The ETM+ is a multispectral scanning radiometer that is carried on the Landsat 7 satellite. The ETM+ radiometer provides data from eight spectral bands and can be ordered in varying levels of calibration. Systematic correction Level 1G images were used for this report. The Level 1G product incorporates both a radiometric and geometric correction to images. The images are rotated to north, aligned, coarsely georeferenced to the Universal Transverse Mercator (UTM) projection, and resampled to 28.5-meter pixel resolution using a nearest neighbor algorithm (Research Systems Incorporated, 2001). Two of the spectral bands are eliminated from processing: spectral band 1 because of data redundancy and thermal spectral band 6 because it measures transmitted energy (the other bands measure reflected energy).

The images were referenced to the UTM projection and projected to fit the Albers equal-area projection. Individual image scenes were merged and cropped to the basin boundary to speed and facilitate processing. The final classification images consisted of three composite images for the study area two in early spring to map winter wheat and one in summer to map the remaining crops. Mapping of land use and irrigated croplands was done in two stages. The first stage consisted of determining land use, the second stage consisted of determining specific irrigated crops.

Ground-reference data were compiled from FSA and NRCS county offices for each county in the basin using a ran-

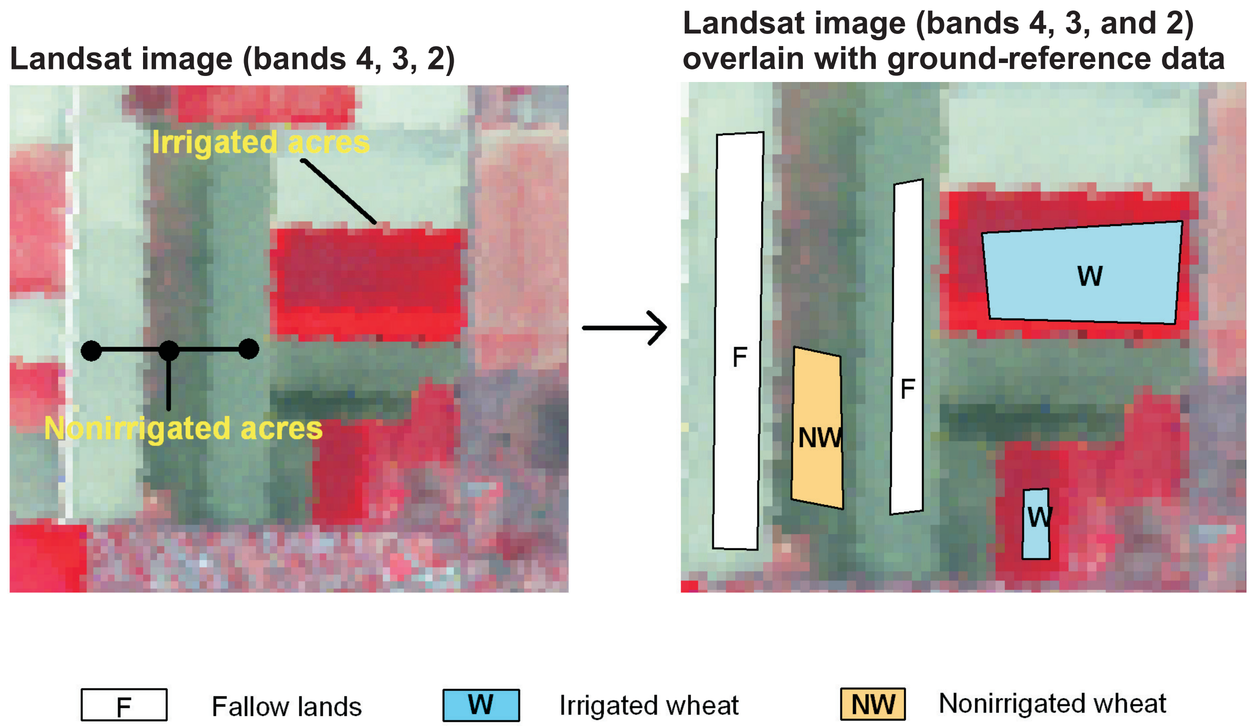

Figure 4. Example of ground-reference data used to overlay and classify imagery.

dom approach. A random selection of points was generated for areas known to be, or thought to be, irrigated in the drainage basin. Maps of these areas were sent to each FSA county office in the drainage basin. County offices were asked to identify the crop types and irrigation status. The data were generally provided as an annotated photocopy of the office aerial photograph of the particular field in question. The field boundaries were then digitized using the satellite image and annotated with the comments provided by the FSA office (fig. 4). Half of the returned ground-reference data were used in the generation of training signatures and the other half were used for accuracy assessment at the end of the analysis.

Accuracy Assessment

An accuracy assessment of the cell classifications was completed for the drainage basin using ground-reference data. Segments from four counties (Beckham, Carson, Gray, and Greer) were used for the assessment. Confusion matrices (probability matrices of land-use classes) were generated using the final classified image and the accuracy segments. An accuracy of 69.6960 percent with a kappa coefficient of 0.0007 was achieved. The low kappa coefficient was a result of the low number of accuracy segments and the lack of representation of all classes in the final classified image. In addition to the class confusion matrix, errors of commission/omission, producer and user accuracies also were examined.

Suggestions to Increase Accuracy

Two of the primary determinants of accuracy in defining irrigated crops are the dates of the Landsat images and number of the ground-reference data samples. To correlate the peak growth of individual crops with the best Landsat image date, there must be sufficient ground-truth data regarding the distribution of crop types and irrigation practices. Required information includes: (1) date of planting and harvest in order to interpolate the dates of peak growth and greenness, and (2) number of harvested acres for each crop by county to determine the number of ground-truth data to collect for each crop. With knowledge of peak greenness of each crop in a given season, the number of Landsat image dates can be better determined. For example, the peak greenness for corn during the 2000 growing season may have been in mid-June, but peak greenness for soybeans may have been in early June. In that case, two Landsat image dates would be required to achieve the greatest accuracy in determining irrigated crops.

Limitations of Landsat

Even with the correct date selection and ground-reference data, there are limitations to using Landsat multispectral satellite imagery because of limitations of spectral range and spatial resolution (5 multispectral bands at 30-meter spatial resolution). Some agricultural crops or vegetation species are too spectrally similar to be differentiated by Landsat. Hyperspectral sensors with broader spectral ranges and higher spatial resolutions may enable greater distinction of vegetation classes. With multispectral sensors such as Landsat, there are only 5 broad spectral bands (0.45 – 1.75 micrometers (µm)) of recorded information; hyperspectral sensors can range from 36 to 224 spectral bands (0.45 – 2.5 µm) of recorded information. With increased spectral range and spatial resolution, it is possible to identify subtle changes in chlorophyll absorption that relate to different vegetation species and health of a vegetation species. Currently, most hyperspectral sensors are on airborne platforms such as Advanced Visible Infrared Imaging Spectrometer (AVIRIS) and Compact Airborne Spectrographic Imager (CASI), but the number of satellite-borne hyperspectral platforms such as Hyperion are increasing. Presently (2002), there are two high spatial-resolution satellites (IKONOS and QUICKBIRD) with 4-meter multi-spectral sensors.

Remotely Sensed Irrigated Crop Acres

Remotely sensed irrigated crop acres were determined for portions of the following Oklahoma counties in the Lake Altus drainage basin: Beckham, Greer, Kiowa, Roger Mills, and Washita. Beckham County had the greatest number of irrigated crop acres, followed by Roger Mills, Greer, Kiowa, and Washita (table 4). Alfalfa, peanuts, and wheat were the only crops determined to be irrigated in the five counties. Irrigated acres of alfalfa, peanuts, and wheat were greatest in Beckham County. A total of 70 percent of irrigated wheat, 68 percent of irrigated alfalfa, and 51 percent of irrigated peanuts in the Oklahoma counties occurred in Beckham County.

Remotely sensed irrigated crop acres were determined for the following Texas counties: Carson, Donley, Gray, Potter, and Wheeler. Although a small portion of Randall County is included in the drainage basin, there were no reported irrigated crop acres in that county. Carson County had the greatest number of irrigated crop acres followed by Gray, Wheeler, Potter, and Donley (table 4). Irrigated acres of corn, sorghum, soybeans, and wheat were greatest in Carson County. A total of 92 percent of irrigated sorghum, 63 percent of irrigated corn, 51 percent of irrigated wheat, and 49 percent of irrigated soybeans in Texas counties occurred in Carson County. Wheeler County had the largest number of irrigated alfalfa acres, representing 94 percent of the irrigated alfalfa in Texas counties.

Seventy-four percent of the total irrigated crop acreage in the drainage basin occurred in Texas counties. One hundred percent of irrigated corn, sorghum, and soybeans in the drainage basin occurred in Texas. Eighty-nine percent or 38,677 acres of irrigated wheat occurred in Texas. Irrigated peanuts and irrigated alfalfa acres were greater in Oklahoma than in Texas. Eighty-one percent or 13,768 acres of irrigated alfalfa and 71 percent or 1,583 acres of irrigated peanuts were in Oklahoma.

There were 43,686 acres of irrigated wheat, or 56 percent of the total irrigated crop acres in the drainage basin (fig. 5). Irrigated alfalfa consisted of 22 percent of the total irrigated crop acres in the drainage basin, irrigated corn consisted of 11 percent, and irrigated soybeans consisted of 6 percent. The remaining 5 percent of irrigated crop acres in the drainage basin consisted of peanuts and sorghum.

Irrigated crop acres from state water boards

Irrigated crop acres from the OWRB and the TWDB were compiled and summarized for the 2000 growing season. The OWRB collects irrigation information in Oklahoma about specific irrigated crops by county and by 8-digit HUC watershed. Mail survey forms are sent out annually to registered water users. Approximately 66 percent of registered water users complete and return the irrigation surveys sent out by the OWRB (Phyllis Robertson, Oklahoma Water Resources Board, oral commun., 2002). Irrigated acres from the OWRB were compiled for portions of Oklahoma counties in the Lake Altus drainage basin (fig. 1) (Phyllis Robertson, Oklahoma Water Resources Board, written commun., 2002).

The TWDB collects water use and irrigation information for Texas using two survey compilation methods. The first survey reporting method collects information annually regarding the sum of irrigated acres in a county and by 8-digit HUC watershed, but not specific information about individual crops that are irrigated. The second survey is a detailed irrigation survey and is a cooperative effort between the NRCS, U.S. Department of Agriculture, the Texas State Soil and Water Conservation Board, and the TWDB. This detailed survey is conducted at 5-year intervals (Texas Water Development Board, 2000). Specific information about irrigated crop acres are recorded on a countywide basis, but not on a watershed basis. A detailed irrigation survey was conducted in Texas counties during the 2000 growing season.

Irrigated crop acres in the drainage basin for Donley, Gray, Potter, Randall, and Wheeler Counties in Texas were determined by dividing the portion of drainage basin in a county by the total area of the county and multiplying the result by the total irrigated crop acres in each county. Because the majority of irrigation in Carson County occurred in and around the drainage basin, a boundary was digitized outlining the area in Carson County where the majority of agriculture was present and irrigation was being applied. The irrigated crop acres in the drainage basin for Carson County were determined by dividing the portion of the drainage basin in the county by the digitized area instead of the total area of Carson County and multiplying

Table 4. Irrigated crop acres derived from remote sensing techniques and Landsat imagery for portions of counties in the Lake Altus drainage basin during the 2000 growing season

[–, not determined]

Counties	State	Irrigated crops (acres)						
		Alfalfa	Corn	Peanuts	Sorghum	Soybeans	Wheat	Total
Beckham	Okla.	9,297	–	807	–	–	3,490	13,594
Greer	Okla.	1,719	–	225	–	–	599	2,543
Kiowa	Okla.	691	–	225	–	–	440	1,356
Roger Mills	Okla.	2,003	–	315	–	–	470	2,788
Washita	Okla.	58	–	11	–	–	10	79
Total	**Okla.**	**13,768**	**0**	**1,583**	**0**	**0**	**5,009**	**20,360**
Carson	Tex.	1	5,573	0	1,897	2,360	19,650	29,481
Donley	Tex.	0	200	0	1	66	55	322
Gray	Tex.	187	2,792	0	149	1,407	11,986	16,521
Randall	Tex.	–	–	–	–	–	–	–
Potter	Tex.	1	1	0	7	42	2,239	2,290
Wheeler	Tex.	3,002	266	646	15	962	4,747	9,638
Total	**Tex.**	**3,191**	**8,832**	**646**	**2,069**	**4,837**	**38,677**	**58,252**
Basin Total		**16,959**	**8,832**	**2,229**	**2,069**	**4,837**	**43,686**	**78,612**

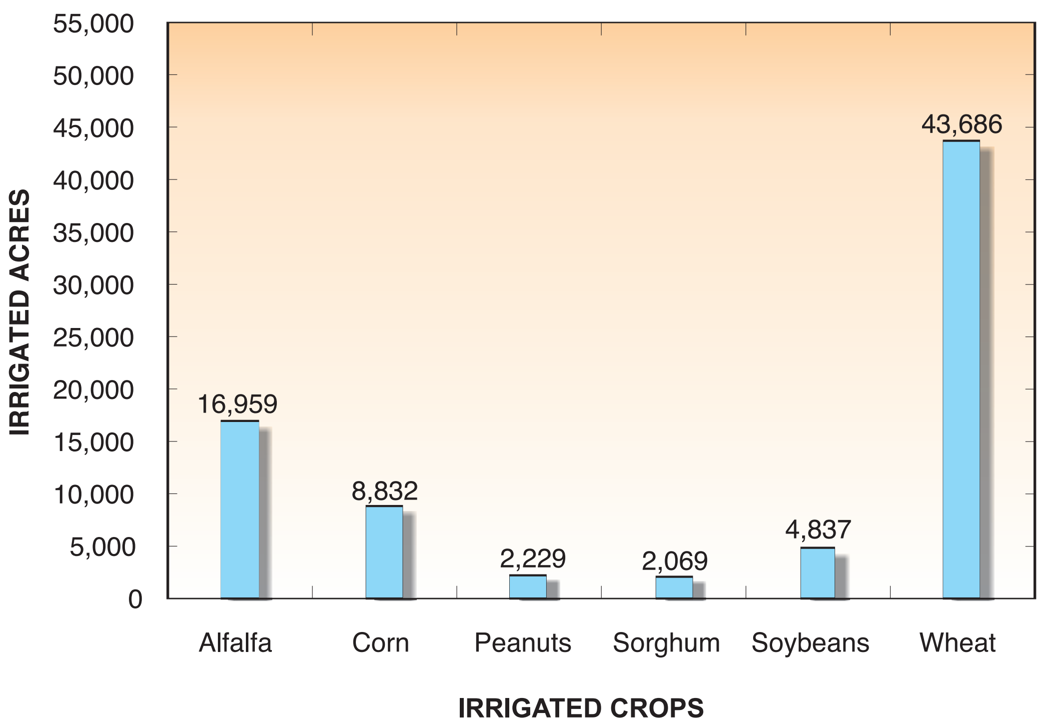

Figure 5. Irrigated crop acres in the Lake Altus drainage basin during the 2000 growing season, determined using remote-sensing techniques and Landsat imagery,

the result by the total irrigated crop acres in the county.

In the Oklahoma portion of the drainage basin, Beckham County had the greatest number of reported irrigated crop acres, followed by Greer, Kiowa, and Roger Mills (table 5). There were no irrigated crop acres reported for the portion of Washita County in the drainage basin. Alfalfa, corn, cotton, hay, peanuts, sorghum, and wheat were reported irrigated in the five Oklahoma counties. A total of 69 percent of irrigated hay, 64 percent of irrigated sorghum, 62 percent of irrigated peanuts, 53 percent of irrigated wheat, and 51 percent of irrigated alfalfa in Oklahoma counties occurred in Beckham County. A total of 99 percent of irrigated corn was reported in Kiowa County with 385 acres. Irrigated cotton was greatest in Roger Mills County, representing 89 percent of the total irrigated cotton reported for Oklahoma counties.

In the Texas portion of the drainage basin, Carson County had the greatest number of reported irrigated crop acres followed by Gray, Wheeler, Potter, Donley, and Randall Counties (table 5). Irrigated acres of alfalfa, corn, sorghum, soybeans, sunflowers, and wheat were greatest in Carson County. A total of 100 percent of irrigated sunflowers, 92 percent of irrigated sorghum, 79 percent of irrigated wheat, 76 percent of irrigated soybeans, 70 percent of irrigated corn, and 66 percent of irrigated alfalfa for Texas counties occurred in Carson County. Irrigated cotton, hay, and peanuts were greatest in Wheeler County. A total of 92 percent of irrigated peanuts, 73 percent of irrigated cotton, and 70 percent of irrigated hay for Texas counties occurred in Wheeler County.

Irrigated crop acres for Texas counties reported by the TWDB were 94 percent of the total reported irrigated acres in the Lake Altus drainage basin (table 5). One hundred percent of irrigated sunflowers and irrigated soybeans, 99 percent of irrigated wheat, 98 percent of irrigated sorghum and corn, and 91 percent of irrigated cotton in the drainage basin occurred in Texas. Only irrigated alfalfa and irrigated peanuts had more acreage in Oklahoma than in Texas (table 5).

There were 46,659 acres of irrigated wheat, or 47 percent of the total irrigated crop acres in the drainage basin (fig. 6). Irrigated corn comprised 17 percent of the total irrigated crop acres in the drainage basin, irrigated soybeans comprised 11 percent, irrigated sorghum comprised 10 percent, and irrigated hay comprised 5 percent. The remaining 10 percent of irrigated crops acres in the drainage basin consisted of peanuts, cotton, alfalfa, and sunflowers.

Irrigation water requirements

The irrigation water requirements is the depth of irrigation water, excluding precipitation, stored soil moisture, or ground water, that is required consumptively for healthy crop production (U.S. Department of Agriculture, 1970). The irrigation water requirement is calculated by subtracting crop evapo-

Table 5. Irrigated crop acres reported from the Oklahoma Water Resources Board and Texas Water Development Board for portions of Oklahoma and Texas Counties in the Lake Altus drainage basin during the 2000 growing season

[–, not reported]

Counties	State	Irrigated crops (acres)									
		Alfalfa	Corn	Cotton	Hay	Peanuts	Sorghum	Soybeans	Sunflowers	Wheat	Total
Beckham	Okla.	672	2	10	784	1,561	116	–	–	133	3,278
Greer	Okla.	536	0	15	100	797	0	–	–	60	1,508
Kiowa	Okla.	0	385	0	98	156	65	–	–	58	762
Roger Mills	Okla.	100	0	210	150	0	0	–	–	0	460
Washita	Okla.	–	–	–	–	–	–	–	–	–	–
Total	**Okla.**	**1,308**	**387**	**235**	**1,132**	**2,514**	**181**	**0**	**0**	**251**	**6,008**
Carson	Tex.	663	11,182	488	495	0	8,551	8,228	2,172	36,850	68,629
Donley	Tex.	30	16	75	33	43	33	7	0	34	271
Gray	Tex.	236	4,417	43	493	0	649	2,611	0	7,756	16,205
Potter	Tex.	79	24	14	79	0	29	0	0	185	410
Randall	Tex.	1	3	2	2	0	19	0	0	25	52
Wheeler	Tex.	0	300	1,711	2,612	506	60	0	0	1,558	6,747
Total	**Tex.**	**1,009**	**15,942**	**2,333**	**3,714**	**549**	**9,341**	**10,846**	**2,172**	**46,408**	**92,314**
Basin Total		**2,317**	**16,329**	**2,568**	**4,846**	**3,063**	**9,522**	**10,846**	**2,172**	**46,659**	**98,322**

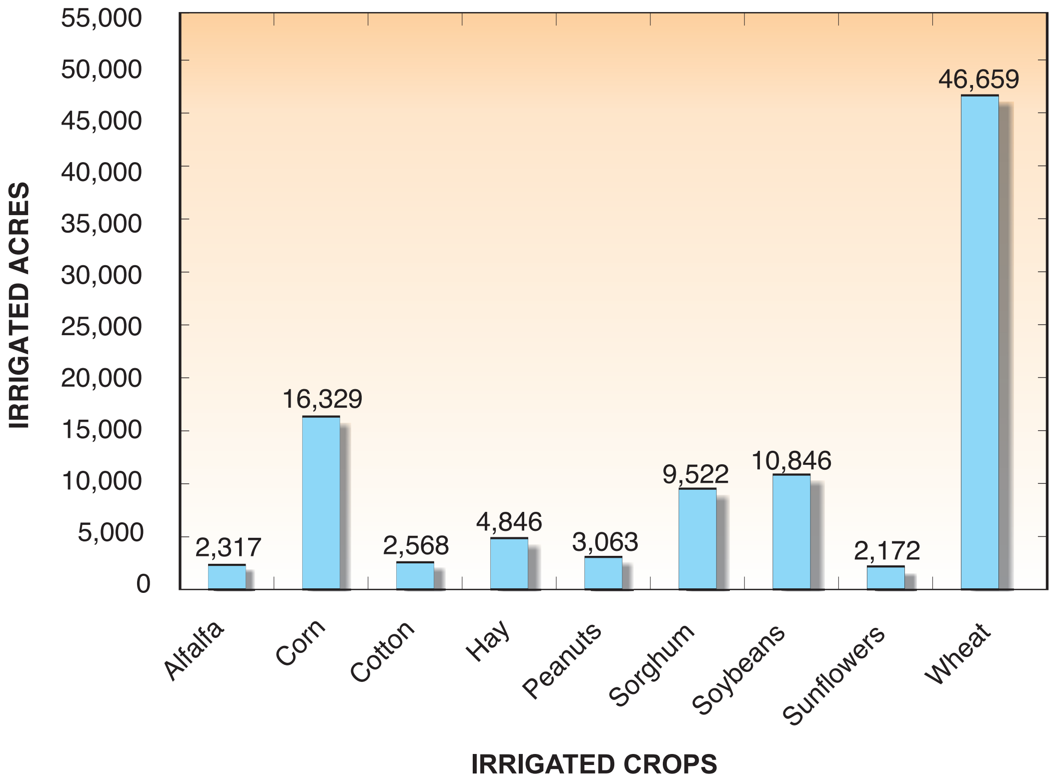

Figure 6. Irrigated crop acres in the Lake Altus drainage basin during the 2000 growing season, reported from the Oklahoma Water Resources Board and the Texas Water Development Board.

transpiration by the amount of water available to the crop through natural precipitation.

Climate conditions during the 2000 growing season were extremely dry and hot in most of the study area and were not representative of a typical growing season in the drainage basin. Most of the precipitation occurred in March and June, with little or no precipitation occurring in July, August, and September. During July and August, average monthly temperatures ranged from 80 degrees Fahrenheit in Roger Mills County to 90 degrees Fahrenheit in Kiowa County (Howard Johnson, Oklahoma Climatological Survey, written commun., 2001). There were several consecutive days in July, August, and September where temperatures exceeded 100 degrees Fahrenheit (Weldon E. Sears, Natural Resources Conservation Service, oral commun., 2002). Based on the extremely hot and dry weather conditions during the 2000 growing season, estimates of irrigation water use presented in this report are probably greater than for a normal year. The values of irrigation water use in this report are a measure of how much water crops could consume if it were available during the growing season. Climate data from September 1999 to October 2000 were used from weather stations listed in table 6.

Although the evapotranspiration model used for this report can accurately predict evapotranspiration in 5-day increments or longer in arid and non-humid environments (U.S. Department of Agriculture, 1993), other factors and assumptions made while calculating crop evapotranspiration and irrigation water requirements should be considered. Other factors such as irrigation practices, soil properties, water stress factors, and soil evaporation that affect crop water use were not considered when computing crop evapotranspiration for this report. The actual soil intake rate and the rainfall intensities were not considered when calculating the effective precipitation. A soil water storage factor of 1 was used to calculate the effective precipitation values used in this report. A soil water storage factor of 1 refers to a 3-inch available soil water capacity in the crop root zone.

The steps used to calculate the irrigation water requirements in this report include: (1) calculation of a referenced evapotranspiration; (2) determination of crop evapotranspiration, and (3) calculation of effective precipitation. The following sections provide an overview of the steps used to calculate irrigation water requirements.

Reference Evapotranspiration

An evapotranspiration model developed by Doorenbos and Pruitt (1977), based on climate data from September 1999 through October 2000, was used to calculate seasonal estimates of reference evapotranspiration (table 7) for major crops during the 2000 growing season. The reference evapotranspiration

Table 6. Weather stations used in study, climate data from September 1999 to October 2000

U.S. Weather Service weather stations			Oklahoma Mesonet weather stations		
Counties	State	Station name	Counties	State	Station name
BECKHAM	Okla.	ELK CITY	ROGER MILLS	Okla.	Cheyenne (CHEY)
BECKHAM	Okla.	ERICK	BECKHAM	Okla.	Erick (ERIC)
BECKHAM	Okla.	MORAVIA	WASHITA	Okla.	Retrop (RETR)
BECKHAM	Okla.	RETROP	KIOWA	Okla.	Hobart (HOBA)
BECKHAM	Okla.	SAYRE	GREER	Okla.	Mangum (MANG)
BECKHAM	Okla.	SWEETWATER	Texas A&M Agriculural Research and Extension Center weather stations		
GREER	Okla.	MANGUM	County	State	Station name
GREER	Okla.	WILLOW	CARSON	Tex.	White deer
KIOWA	Okla.	ALTUS DAM			
KIOWA	Okla.	HOBART			
KIOWA	Okla.	ROOSEVELT			
KIOWA	Okla.	SEDAN			
KIOWA	Okla.	SNYDER			
ROGER MILLS	Okla.	HAMMON			
ROGER MILLS	Okla.	REYDON			
WASHITA	Okla.	COLONY			
WASHITA	Okla.	CORDELL			
CARSON	Tex.	PANHANDLE			
DONLEY	Tex.	CLARENDON			
GRAY	Okla.	PAMPA			
GRAY	Okla.	MC LEAN			
POTTER	Tex.	AMARILLO			
RANDALL	Tex.	UMBARGER			
RANDALL	Tex.	CANYON			
WHEELER	Okla.	SHAMROCK			
WHEELER	Okla.	WHEELER			

Table 7. Reference evapotranspiration (ET_o) for crop growing seasons in the Lake Altus drainage basin during the 2000 growing season

[–, not determined]

Counties	State	Reference evapotranspiration for crop growing season (inches)								
		Alfalfa	Corn	Cotton	Hay	Peanuts	Sor-ghum	Soy-beans	Sun-flowers	Wheat
Beckham	Okla.	51.5	39.2	38.9	38.9	28.1	33.6	33.6	–	35.8
Greer[1], Kiowa[1], and Washita[1]	Okla.	53.4	41.4	41.4	41.2	30.0	33.6	35.6	–	37.1
Roger Mills	Okla.	52.3	40.4	40.7	44.8	29.6	35.3	35.3	–	35.6
Carson	Tex.	56.7	39.4	43.2	43.2	35.1	33.7	36.8	33.7	40.4
Potter[2]	Tex.	57.9	40.3	44.0	44.0	35.8	34.3	37.4	34.3	41.5
Gray[2]	Tex.	58.1	40.3	44.1	44.1	35.8	34.4	37.5	34.4	42.0
Wheeler[1]	Tex.	52.6	36.1	40.3	40.7	29.2	31.9	34.8	–	36.5

[1]Climate data from Beckham County was used to calculate reference evapotranspiration.

[2]Solar radiation data from Carson County was used to calculate reference evapotranspiration.

values differ due to the variable length of growing seasons for different crops. Average monthly values of precipitation, barometric pressure, relative humidity, solar radiation, temperature, and wind speed data were used to calculate reference evapotranspiration from October 1999 to September 2000. The Oklahoma Climatological Survey (OCS) provided climate data from multiple weather stations from the National Weather Service and the Oklahoma Mesonet to create monthly averages for portions of counties in the study area (Howard Johnson, Oklahoma Climatological Survey, written commun., 2001) (table 6). Additional solar radiation and barometric pressure data were acquired from Texas A&M Agricultural Research and Extension Center for Carson, Gray, and Potter Counties in Texas (U.S. Department of Agriculture, 2001).

The model by Doorenbos and Pruitt (1977) is referred to as the radiation method, which is very accurate in arid and subhumid areas (U.S. Department of Agriculture, 1993). The radiation method requires that a reference evapotranspiration rate (ET_o) be calculated and adjusted by a basal crop coefficient to compute the rate of evapotranspiration for a specific crop (crop evapotranspiration ET_c). Reference evapotranspiration (ET_o) is a baseline rate of evapotranspiration for a clipped grass growing under climatic conditions for a known time period. The radiation method from Doorenbos and Pruitt (1977) is expressed by equation 1:

$$ET_o=-0.012+(\Delta/\Delta+\Upsilon)*b_r*R_s/\lambda \quad (1)$$

where

ET_o = reference evapotranspiration for a clipped grass, in inches;

Δ = slope of the vapor pressure curve, in millibars per degree Fahrenheit;

Υ = psychrometric constant, in millibars per degree Fahrenheit;

b_r = adjustment factor depending on the average relative humidity and daytime wind speed, in miles per day;

R_s = incoming solar radiation in langleys per day; and

λ = heat of vaporization of water, in langleys per day

Crop Evapotranspiration

Crop evapotranspiration (ET_c) is an empirical estimate of the total amount of water required for a crop growing in an area under known climate conditions so that crop production is not limited by lack of water. Crop evapotranspiration is determined by adjusting the reference evapotranspiration (ET_o) to fit a basal crop coefficient curve. A basal crop coefficient curve represents the water use of a healthy, well-watered crop where the soil surface is dry (U.S. Department of Agriculture, 1993). The crop coefficient system developed by Doorenbos and Pruitt (1977) and modified by Howell and others (1986) was used to calculate monthly estimates of crop evapotranspiration (ET_c) for the nine major crops being irrigated during the 2000 growing season. Crop evapotranspiration (ET_c) is calculated using the reference evapotranspiration (ET_o) and a basal crop coefficient (K_{cb}). The formula used to calculate crop evapotranspiration is expressed by equation 2 (U.S. Department of Agriculture, 1993; Doorenbos and Pruitt, 1977):

$$ET_c=K_{cb}*ET_o \quad (2)$$

where

ET_c = rate of crop evapotranspiration, in inches;

K_{cb} = basal crop coefficient relating actual crop evapotranspiration (ET_c) to reference evapotranspiration (ET_o); and

ET_o = reference evapotranspiration for a clipped grass reference crop, in inches

The basal crop coefficient (K_{cb}) is a factor that relates reference evapotranspiration (ET_o) to actual crop evapotranspiration (ET_c). The method outlined by Doorenbos and Pruitt (1977) divides the growing season for a particular crop into four growing stages and calculates multiple basal crop coefficients at defined increments throughout each growing stage using equations and parameters in U.S. Department of Agriculture (1993, fig. 2-21 and table 2-20). Crop evapotranspiration for the growing season was calculated for alfalfa, corn, cotton, hay, peanuts, sorghum, soybeans, sunflowers, and wheat for portions of counties in the Lake Altus drainage basin (table 8).

Effective Precipitation

Effective precipitation (f_e) is the amount of precipitation that is available to meet the evapotranspiration requirements of crops. Monthly average values of precipitation for each county of the drainage basin from September 1999 to October 2000 were provided by the OCS (Howard Johnson, Oklahoma Climatological Survey, written commun., 2001) and were used to calculate effective precipitation. Equation 3 was used to calculate effective precipitation (f_e) (U.S. Department of Agriculture, 1970):

$$f_e=(0.7091747*r_t^{0.82416}-0.11556)*(10^{0.02426*ETc})*f \qquad (3)$$

where

f_e = average monthly effective precipitation, in inches;

r_t = average monthly precipitation, in inches;

ET_c = rate of crop evapotranspiration, in inches; and

f = soil water storage factor (dimensionless)

Determination of Irrigation Water Requirements

The irrigation water requirement (U) is calculated by subtracting the amount of water available to the crop through natural precipitation (effective precipitation, f_e) from the crop evapotranspiration (ET_c). Irrigation water requirements (U) for the growing season were calculated on a countywide basis for each of the irrigated crops (table 9). The formula used to calculate irrigation water requirement is expressed by equation 4 (U.S. Department of Agriculture, 1970):

$$U=ET_c-f_e \qquad (4)$$

where

U = irrigation water requirement, in inches;

ET_c = rate of crop evapotranspiration, in inches; and

f_e = effective precipitation, in inches

Table 8. Crop evapotranspiration (ET_c) for major crops in the Lake Altus drainage basin during the 2000 growing season

[–, not determined]

Counties	State	Crop evapotranspiration for crop growing season (inches)								
		Alfalfa	Corn	Cotton	Hay	Peanuts	Sorghum	Soybeans	Sunflowers	Wheat
Beckham	Okla.	38.9	31.0	33.6	29.1	20.9	27.0	28.8	–	26.5
Greer[1], Kiowa[1], and Washita[1]	Okla.	40.3	33.0	35.5	30.8	22.2	28.5	30.3	–	27.1
Roger Mills	Okla.	39.7	32.3	35.4	32.2	22.2	28.6	30.3	–	25.9
Carson	Tex.	42.9	31.0	37.0	32.1	26.5	26.8	31.5	27.4	30.3
Potter	Tex.	43.8	31.6	37.6	32.7	27.0	27.3	32.1	27.9	31.2
Gray	Tex.	43.9	31.6	37.8	32.7	27.1	27.0	32.2	28.0	42.0
Wheeler	Tex.	39.8	28.8	34.9	30.5	21.8	25.5	29.8	–	26.7

[1]Climate data from Beckham County was used to calculate crop evapotranspiration.

Table 9. Irrigation water requirements (U) for major crops in the Lake Altus drainage basin during the 2000 growing season

[–, not determined]

Counties	State	Irrigation water requirements (inches)								
		Alfalfa	Corn	Cotton	Hay	Peanuts	Sorghum	Soybeans	Sunflowers	Wheat
Beckham	Okla.	27.1	22.8	27.3	21.9	18.7	24.2	26	–	16.6
Greer, Kiowa, and Washita	Okla.	26.7	23.8	28.2	17.2	18.9	24.4	26.2	–	17.2
Roger Mills	Okla.	28.6	24.7	29.6	24.8	19.9	25.4	27.2	–	16
Carson	Tex.	31.8	22.4	30.0	24.0	24.2	23.8	27.6	24.2	23.8
Potter	Tex.	34.9	25.9	32.1	26.4	24.7	24.7	29.7	26.1	25.5
Gray	Tex.	31.6	22.0	30.5	24.8	24.8	24.5	28.3	25.1	22.6
Wheeler	Tex.	29	20.8	29.1	23.7	19.9	23.6	27.2	18.5	18.5

Irrigation Water Use Calculated From Remotely Sensed Irrigated Crop Acres

Irrigation water use is defined as the amount of water supplied through irrigation so that crop yields are not limited. Empirical estimates of irrigation water use for the 2000 growing season were calculated as the product of the irrigation water requirements (table 9) and irrigated crop acres determined from remote-sensing techniques (table 4).

An estimated total of 154,920 acre-feet of water were used for irrigation in the Lake Altus drainage basin during the 2000 growing season (table 10). Seventy-four percent of the irrigation water use in the drainage basin occurred in Texas counties (table 10). Irrigation water use was greatest in Carson County, Texas, with an estimated 58,555 acre-feet or 38 percent of irrigation water use in the drainage basin (table 10). Gray County accounted for 21 percent of irrigation water use in the drainage basin; whereas, Wheeler County accounted for 12 percent of irrigation water use. Irrigation water use for the portion of the drainage basin in Oklahoma was greatest in Beckham County with an estimated 27,076 acre-feet or 17 percent of the total irrigation water use in the drainage basin (table 10).

Irrigation water use was greatest for wheat, with an estimated 80,692 acre-feet, or 52 percent of the total irrigation water use in the drainage basin (fig. 7). Irrigation water use for alfalfa was 39,011 acre-feet, or 25 percent of the total irrigation water use. The distribution of irrigation water use for other crops in the drainage basin was 11 percent corn and 7 percent soybeans, with peanuts and sorghum making up the remaining 5 percent. Irrigation water use for corn, sorghum, soybeans, and wheat was greatest in Carson County, Texas; whereas, most of the irrigation water use for alfalfa and peanuts occurred in Beckham County, Oklahoma (table 10).

Irrigation Water Use Calculated From State Reported Irrigated Acres

Irrigation water use for the 2000 growing season was calculated as the product of the irrigation water requirements (table 9) and reported irrigated crop acres from the OWRB and TWDB (table 5). An estimated total of 196,026 acre-feet of water were used for irrigation in the Lake Altus drainage basin during the 2000 growing season (table 11). Ninety-four percent of the total irrigation water use in the drainage basin occurred in Texas. Irrigation water use was greatest in Carson County, with an estimated 138,180 acre-feet, or 70 percent of the total irrigation water use in the drainage basin (table 11). Gray County accounted for 16 percent of irrigation water use in the drainage basin; whereas, Wheeler County accounted for 7 percent of irrigation water use. Irrigation water use for Oklahoma counties was greatest in Beckham County, with an estimated 5,830 acre-feet, accounting for 3 percent of irrigation water use in the drainage basin.

Irrigation water use was greatest for wheat, with an estimated 90,955 acre-feet, or 46 percent of irrigation water use in the drainage basin (fig. 8). Irrigation water use for corn was 30,329 acre-feet, or 15 percent of the irrigation water use in the drainage basin. The distribution of irrigation water use for other crops was 13 percent soybeans, 10 percent sorghum, and 5 percent hay, with alfalfa, cotton, peanuts, and sunflowers making

Table 10. Irrigation water use for portion of counties in the Lake Altus drainage basin during the 2000 growing season, calculated from remotely sensed irrigated acres

[–, not determined]

Counties	State	Irrigation water use (acre-feet)						
		Alfalfa	Corn	Peanuts	Sorghum	Soybeans	Wheat	Total
Beckham	Okla.	20,986	–	1,259	–	–	4,831	27,076
Greer	Okla.	3,826	–	355	–	–	858	5,039
Kiowa	Okla.	1,538	–	344	–	–	629	2,511
Roger Mills	Okla.	4,771	–	521	–	–	628	5,920
Washita	Okla.	129	–	17	–	–	14	160
Total	**Okla.**	**31,250**	–	**2,496**	–	–	**6,960**	**40,706**
Carson	Tex.	3	10,397	0	3,767	5,426	38,962	58,555
Donley	Tex.	0	366	0	2	156	104	628
Gray	Tex.	492	5,117	0	304	3,318	22,606	31,837
Randall	Tex.	3	2	0	17	103	4,755	4,880
Potter	Tex.	–	–	–	–	–	–	–
Wheeler	Tex.	7,263	460	1,073	30	2,183	7,305	18,314
Total	**Tex.**	**7,761**	**16,342**	**1,073**	**4,120**	**11,186**	**73,732**	**114,214**
Basin Total		**39,011**	**16,342**	**3,569**	**4,120**	**11,186**	**80,692**	**154,920**

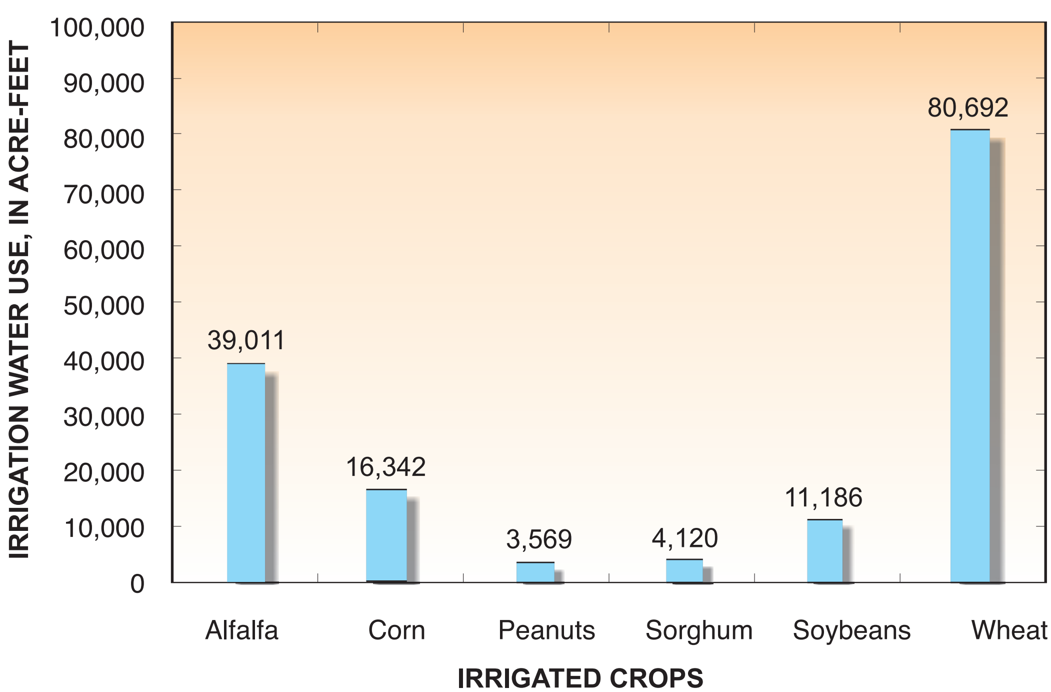

Figure 7. Irrigation water use for crops in the Lake Altus drainage basin during the 2000 growing season, calculated from remotely sense irrigated acres.

Table 11. Irrigation water use for portion of counties in the Lake Altus drainage basin during the 2000 growing season, calculated from irrigated acres reported from Oklahoma Water Resources Board and the Texas Water Development Board

[–, not determined]

Counties	State	Irrigation water use (acre-feet)									
		Alfalfa	Corn	Cotton	Hay	Peanuts	Sorghum	Soybeans	Sunflowers	Wheat	Total
Beckham	Okla.	1,517	4	23	1,433	2,435	234	–	–	184	5,830
Greer	Okla.	1,193	0	35	186	1,259	0	–	–	86	2,759
Kiowa	Okla.	0	764	0	182	246	132	–	–	83	1,407
Roger Mills	Okla.	238	0	517	310	0	0	–	–	0	1,065
Washita	Okla.	–	–	–	–	–	–	–	–	–	–
Total	**Okla.**	**2,948**	**768**	**575**	**2,111**	**3,940**	**366**	**0**	**0**	**353**	**11,061**
Carson	Tex.	1,755	20,861	1,220	992	0	16,978	18,920	4,386	73,068	138,180
Donley	Tex.	79	29	190	68	89	67	17	0	64	603
Gray	Tex.	621	8,094	109	1,018	0	1,322	6,156	0	14,628	31,948
Randall	Tex.	229	52	38	174	0	62	0	0	393	948
Potter	Tex.	3	6	5	4	0	39	0	0	52	109
Wheeler	Tex.	0	519	4,148	5,154	841	118	0	0	2,397	13,177
Total	**Tex.**	**2,687**	**29,561**	**5,710**	**7,410**	**930**	**18,586**	**25,093**	**4,386**	**90,602**	**184,965**
Basin Total		**5,635**	**30,329**	**6,285**	**9,521**	**4,870**	**18,952**	**25,093**	**4,386**	**90,955**	**196,026**

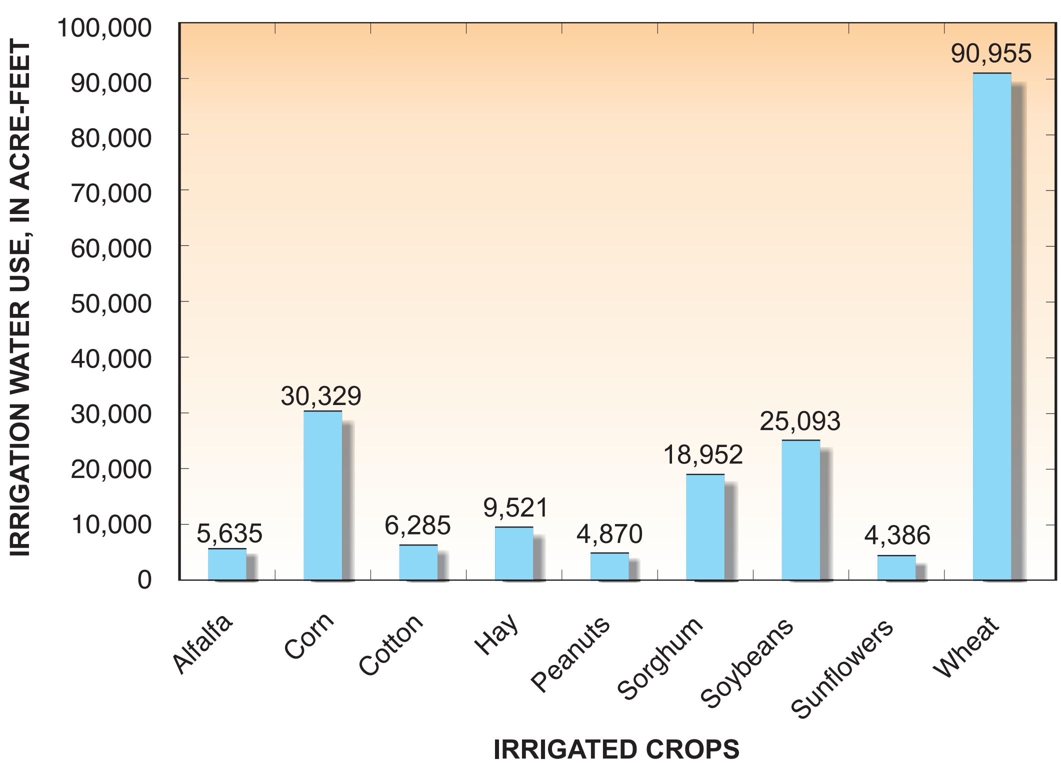

Figure 8. Irrigation water use for crops in the Lake Altus drainage basin during the 2000 growing season, calculated from irrigated acres reported from the Oklahoma Water Resources Board and the Texas Water Development Board.

up the remaining 11 percent of the irrigation water use. Irrigation water use for alfalfa, corn, sorghum, soybeans, sunflowers, and wheat was greatest in Carson County, Texas; whereas, irrigation water use for cotton and hay was greatest in Wheeler County, Texas (table 11). Irrigation water use for peanuts was greatest in Beckham County, Oklahoma.

Comparison of Irrigation Water Use Calculated From Remotely Sensed Irrigated Acres With Irrigation Water Use Calculated From State Reported Irrigated Acres

Estimates of irrigation water use determined from remotely sensed irrigated acres were different than those derived from irrigated crop acres reported by the OWRB and TWDB (figs. 9 and 10). The total volume of water used for irrigation calculated from remotely sensed acres was 154,920 acre-feet (table 10); whereas, irrigation water use calculated using irrigated acres from the OWRB and TWDB was 196,026 acre-feet (table 11), a 23 percent difference (p_d). The percent difference is the preferred method to compare two quantities neither of which is known to be correct (University of California, Davis, 2002). Equation 5 was used in this report to calculate percent differences:

$$p_d = \frac{|A - B|}{|A + B| \div 2} \times 100 \qquad (5)$$

where

p_d = percent difference
A = remotely sensed irrigated acres,
B = the state reported irrigated crop acres from the OWRB and the TWDB

The greatest difference of estimated irrigation water use calculated by the two methods was in Carson County, Texas. Irrigation water use for Carson County calculated from the remotely sensed irrigated acres was 58,555 acre-feet (table 10); whereas, irrigation water use calculated from reported irrigated acres from the TWDB was 138,180 acre-feet (table 11, fig. 8), an 81 percent difference. The second greatest difference in irrigation water use occurred in Beckham County, Oklahoma. Irrigation water use for Beckham County calculated from the remotely sensed acres was 27,076 acre-feet; whereas, irrigation water use calculated from reported irrigated acres from the OWRB was 5,830 acre-feet, a 129 percent difference.

Irrigation water use for corn, cotton, hay, peanuts, sorghum, soybeans, sunflowers, and wheat calculated from OWRB and TWDB acres was consistently greater than irrigation water use calculated from remotely sensed irrigated crop acres (fig. 10). Irrigation water use for alfalfa calculated from the remotely sensed irrigated crop acres was 39,011 acre-feet (table 10); whereas, irrigation water use calculated from reported irrigated crop acres from the OWRB and TWDB was 5,635 acre-feet (table 11), a 150 percent difference (fig. 10). Most of the large differences in irrigation water use for alfalfa (19,469 acre-feet) were due to irrigation water use estimates calculated from remotely sensed irrigated acres of alfalfa in Beckham County (table 4). Difficulty in determining irrigated alfalfa probably was caused in part by a very wet spring and early summer in Oklahoma counties. Another possible reason for the differences could be caused by alfalfa being harvested every couple of months. Alfalfa could have been harvested prior to acquisition of imagery used to map irrigated alfalfa. Comparing irrigation water use for corn, sorghum, and wheat calculated from the remotely sensed irrigated crop acres with those calculated from irrigated crop acres reported by the OWRB and TWDB, there was a 60 percent difference for corn, a 129 percent difference for sorghum, and a 77 percent difference for soybeans (fig. 10). Irrigation water use for cotton, hay, and sunflowers was calculated from the OWRB and TWDB reported acres (total of 20,192 acre-feet), but could not be calculated from the remotely sensed acres because they were not successfully identified during the mapping of irrigated acres from remote sensing techniques and Landsat imagery (tables 10 and 11).

This report provides two estimates of irrigation water use calculated using the same evapotranspiration model with identical model parameters. Differences between the two irrigation water use estimates result from differences between the remotely sensed irrigated acres and irrigated acres reported by OWRB and the TWDB. Image date selection is vital to accurately determine irrigated crops. Images are taken from the Landsat ETM+ satellite that rotate back to a specific geographic location every 16 days. By having to determine irrigated acres for a specific growing season and having to acquire imagery as close as possible to maximum greenness for individual crops on a cloud free day, few images were available that could be used to determine irrigated crops. For instance, in Carson County, some harvesting could have occurred just before the date of image acquisition, which would cause irrigated acres to be underestimated. Having several months of above average precipitation preceding the date of image acquisition could cause non-irrigated lands to be classified as irrigated, which would cause irrigated acres to be overestimated, as in Beckham County.

Even with correct date selection, limitations to using Landsat multispectral satellite imagery include spectral range and spatial resolution. Some agricultural crops or vegetation species are too spectrally similar to be differentiated by Landsat. Hyperspectral sensors with broader spectral ranges and resolutions may enable greater distinction of vegetation classes. With multispectral sensors such as Landsat, there are only 5 broad spectral bands of recorded information; hyperspectral sensors can range from 36 to 224 spectral bands of recorded information. With an increased spectral range and resolution, it may be possible to better identify subtle changes in chlorophyll absorption that relate to different vegetation species and health of a vegetation species.

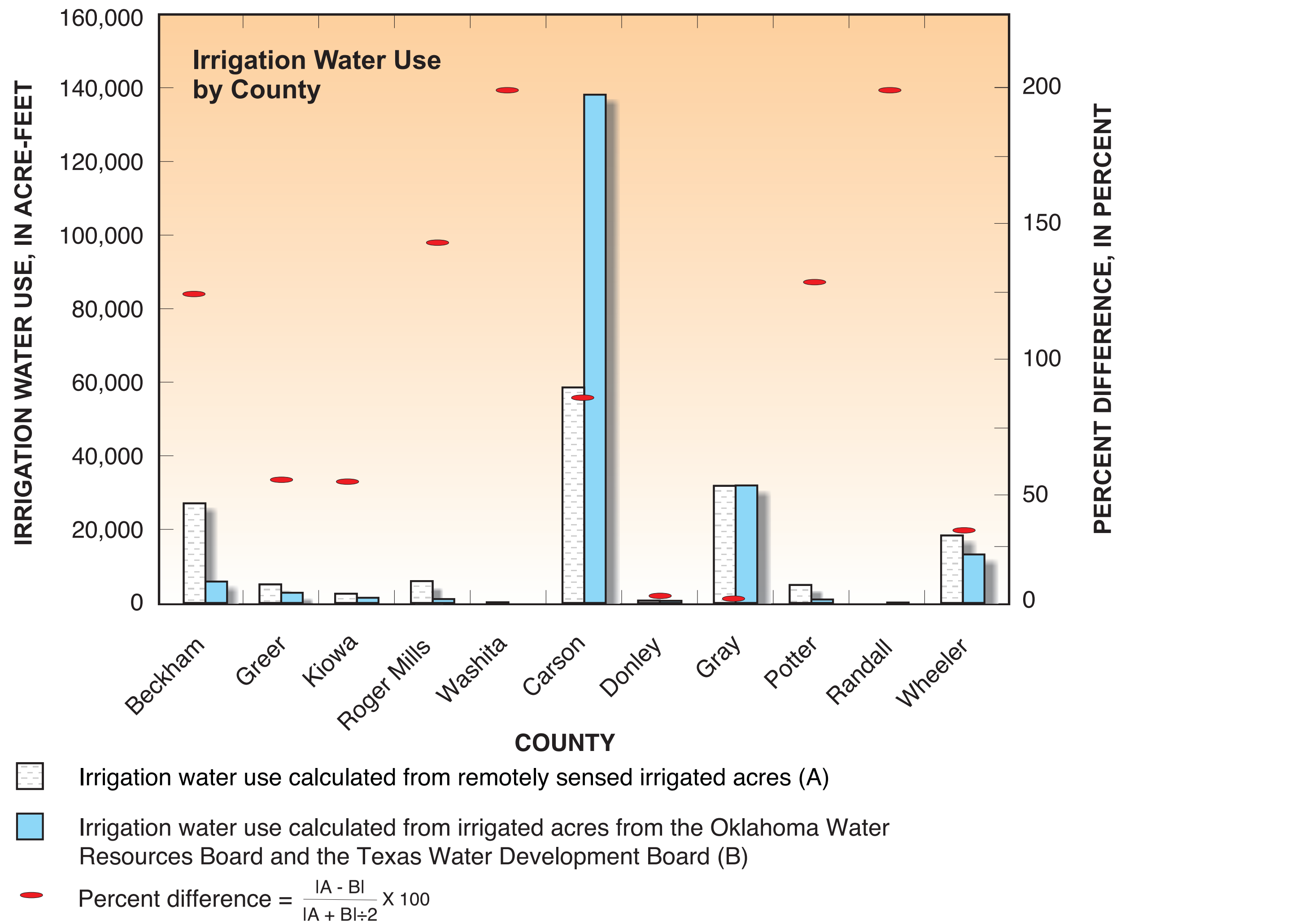

Figure 9. Comparison of irrigation water use calculated from remotely sensed irrigated acres with irrigation water use calculated from irrigated acres reported from the Oklahoma Water Resources Board and Texas Water Development Board in the Lake Altus drainage basin during the 2000 growing season, shown by county,

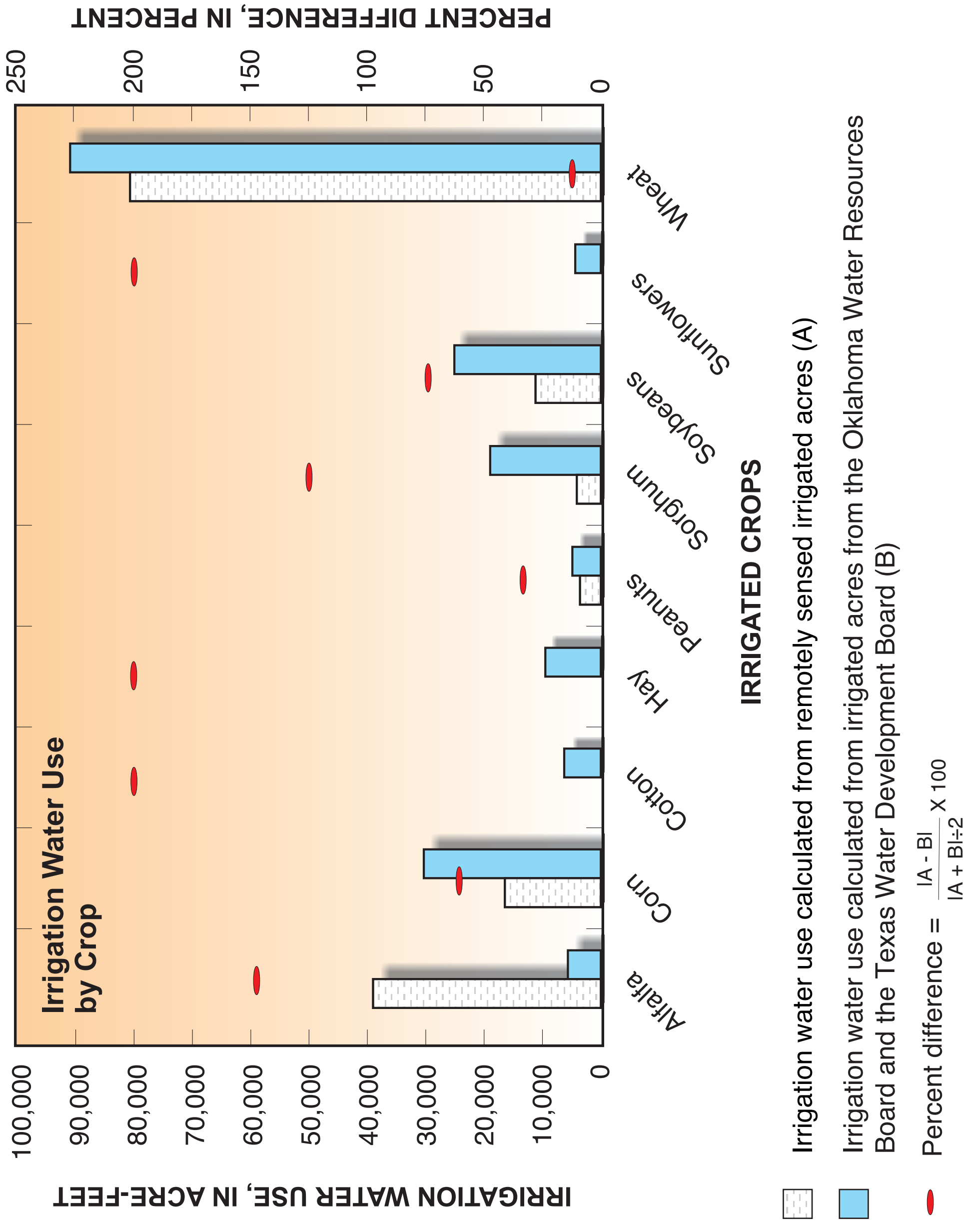

Figure 10. Comparison of irrigation water use calculated from remotely sensed irrigated crop acres with irrigation water use calculated from irrigated acres reported by the Oklahoma Water Resources Board and Texas Water Development Board in the Lake Altus drainage basin during the 2000 growing season, shown by crop.

Summary

Increased demand for water in the Lake Altus drainage basin requires better estimates of water use for irrigation in the drainage basin. The U.S. Geological Survey, in cooperation with the Bureau of Reclamation, investigated new techniques to improve estimates of irrigation water use in the Lake Altus drainage basin. Empirical estimates of reference evapotranspiration, crop evapotranspiration, and crop irrigation water requirements for nine major crops were calculated for the 2000 growing season, September 1999 to October 2000 using a solar radiation-based evapotranspiration model and estimates of irrigated crop acres.

Landsat 7 ETM+ imagery was used to map land use and irrigated crop acres during the 2000 growing season. Land use was mapped using a supervised clustering algorithm based on statistical signatures for 25 pixel classes. Irrigated crop acres were determined using a ratio vegetation index that consisted of a near infrared band divided by a visible red band. A total of 78,612 acres were determined to be irrigated. Beckham County had the greatest number of irrigated crop acres in Oklahoma counties, followed by Roger Mills, Greer, Kiowa, and Washita. Carson County had the largest number of irrigated crop acres in Texas counties, followed by Gray, Wheeler, Potter, and Donley Counties. Seventy-four percent of the total irrigated crop acreage in the drainage basin occurred in Texas counties. One hundred percent of irrigated corn, sorghum, and soybeans in the drainage basin occurred in Texas. Eighty-nine percent or 38,677 acres of irrigated wheat occurred in Texas. Eighty-one percent or 13,768 acres of irrigated alfalfa and 71 percent or 1,583 acres of irrigated peanuts occurred in Oklahoma.

Reported estimates of irrigated crop acres were compiled and summarized for the 2000 growing season from the OWRB and TWDB. A total of 98,322 acres were determined to be irrigated. Beckham County had the greatest number of irrigated crop acres in Oklahoma counties, followed by Greer, Kiowa, and Roger Mills. Carson County had the greatest number of irrigated crop acres in Texas counties, followed by Gray, Wheeler, Potter, Donley, and Randall. Ninety-four percent of the total irrigated crop acres were in Texas counties. One hundred percent of irrigated sunflowers and soybeans, 99 percent of wheat, 98 percent of sorghum and corn, and 91 percent of irrigated cotton in the drainage basin occurred in Texas. Only irrigated alfalfa and irrigated peanuts had more acreage in Oklahoma than in Texas.

According to irrigation water use calculated from the remotely sensed irrigated acres, there was an estimated 154,920 acre-feet of water used for irrigation in the Lake Altus drainage basin during the 2000 growing season. Seventy-four percent of the irrigation water use in the drainage basin occurred in Texas counties. Irrigation water use was greatest for wheat with an estimated 80,692 acre-feet, or 52 percent of the total irrigation water use in the drainage basin. Irrigation water use for alfalfa was 39,011 acre-feet, or 25 percent of the total irrigation water use. Irrigation water use for corn, sorghum, soybeans, and wheat was greatest in Carson County, Texas; whereas, most of the irrigation water use for alfalfa and peanuts occurred in Beckham County.

According to irrigation water use calculated from the state reported irrigated acres, there was an estimated 196,026 acre-feet of water used for irrigation in the Lake Altus drainage basin during the 2000 growing season. Ninety-four percent of the total irrigation water use occurred in Texas. Irrigation water use was greatest for wheat with an estimated 90,955 acre-feet, or 46 percent of irrigation water use in the drainage basin. Irrigation water use for corn was 30,329 acre-feet, or 15 percent of the irrigation water use. Irrigation water use for alfalfa, corn, sorghum, soybeans, sunflowers, and wheat was greatest in Carson County, Texas; whereas, irrigation water use for cotton and hay was greatest in Wheeler County, Texas. Irrigation water use for peanuts was greatest in Beckham County, Oklahoma.

Estimates of irrigation water use calculated from remotely sensed irrigated acres were different than those determined from the state reported irrigated acres. The total volume of water used for irrigation calculated from remotely sensed acres was 154,920 acre-feet; whereas, irrigation water use calculated from the state reported irrigated acres was 196,026 acre-feet, a 23 percent difference. Irrigation water use for Carson County calculated from the remotely sensed acres was 58,555 acre-feet, whereas, irrigation water use calculated from irrigated crop acres reported from the state reported irrigated acres was 138,180 acre-feet, an 81 percent difference. Irrigation water use for alfalfa calculated from the remotely sensed irrigated crop acres was 39,011 acre-feet; whereas, irrigation water use for alfalfa calculated from irrigated crop acres reported from the state reported irrigated acres was 5,635 acre-feet, a 150 percent difference.

Differences between the two irrigation water use estimates result from differences between the remotely sensed irrigated acres and the state reported irrigated acres from the OWRB and the TWDB. By having to determine irrigated acres for a specific growing season and having to acquire imagery as close as possible to maximum greenness for individual crops on a cloud free day, few images are available that could be used to determine irrigated crops.

Even with correct date selection, limitations to using Landsat multispectral satellite imagery include spectral range and spatial resolution. Some agricultural crops or vegetation species are too spectrally similar to be differentiated by Landsat. Hyperspectral sensors with broader spectral ranges and resolutions may enable greater distinction of vegetation classes. With an increased spectral range and resolution, it is possible to identify subtle changes in chlorophyll absorption that relate to different vegetation species and health of a vegetation species. Presently (2002), there are two high spatial-resolution satellites (IKONOS and QUICKBIRD) with 4-meter multi-spectral sensors.

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Appendixes

Appendix 1. Remote sensing classification categories shown with number of pixels and acres for the part of Beckham County, Oklahoma, in the Lake Altus drainage basin during the 2000 growing season

[Null, part of the image that is outside the portion of the drainage basin in the county]

Class name	Code	Pixels	Acres	Percent image
Urban	1	9,883	1,984	0
Water	2	5,282	1,060	0
Clouds	3	235	47	0
Fallow	4	66,745	13,396	2
Grass	5	941,516	188,973	33
Trees	6	164,691	33,055	6
Sunflowers	7	0	0	0
Oat	8	46	9	0
Peanuts	9	21,111	4,237	1
Soybeans	10	0	0	0
Rye	11	4,612	926	0
Cotton	12	1,757	353	0
Sorghum	13	28	6	0
Alfalfa	14	93,383	18,743	3
Corn	15	0	0	0
Wheat	16	213,310	42,814	7
Unknown irrigated crop	17	48,758	9,786	2
Irrigated soybeans	18	1	0	0
Irrigated peanuts	19	4,021	807	0
Cowpeas	20	16,065	3,224	1
Unknown crop	21	7,815	1,569	0
Irrigated alfalfa	22	46,320	9,297	2
Irrigated wheat	23	17,390	3,490	1
Hay/Pasture	24	157,108	31,533	5
Irrigated corn	25	0	0	0
Irrigated sorghum	26	0	0	0
Null	0	1,076,588	216,083	37
Image total		**2,896,665**	**581,393**	**100**

Appendix 2. Remote sensing classification categories shown with number of pixels and acres for the part of Carson County, Texas, in the Lake Altus drainage basin during the 2000 growing season

[Null, part of the image that is outside the portion of the drainage basin in the county]

Class name	Code	Pixels	Acres	Percent image
Urban	1	37,910	7,609	1
Water	2	15,312	3,073	1
Clouds	3	2,044	410	0
Fallow	4	209,717	42,093	7
Grass	5	274,841	55,164	9
Trees	6	198	40	0
Sunflowers	7	23,985	4,814	1
Oat	8	0	0	0
Peanuts	9	0	0	0
Soybeans	10	6,334	1,271	0
Rye	11	13,104	2,630	0
Cotton	12	22	4	0
Sorghum	13	61,544	12,353	2
Alfalfa	14	0	0	0
Corn	15	31	6	0
Wheat	16	294,222	59,054	10
Unknown irrigated crop	17	40,672	8,163	1
Irrigated soybeans	18	11,756	2,360	0
Irrigated peanuts	19	0	0	0
Cowpeas	20	0	0	0
Unknown crop	21	2,881	578	0
Irrigated alfalfa	22	4	1	0
Irrigated wheat	23	97,904	19,650	3
Hay/Pasture	24	189,949	38,125	6
Irrigated corn	25	27,766	5,573	1
Irrigated sorghum	26	9,451	1,897	0
Null	0	1,625,226	326,201	55
Image total		**2,944,873**	**591,069**	**100**

Appendix 3. Remote sensing classification categories shown with number of pixels and acres for the part of Donley County, Texas, in the Lake Altus drainage basin during the 2000 growing season

[Null, part of the image that is outside the portion of the drainage basin in the county]

Class name	Code	Pixels	Acres	Percent image
Urban	1	276	55	0
Water	2	501	101	0
Clouds	3	0	0	0
Fallow	4	1,800	361	0
Grass	5	20,358	4,086	1
Trees	6	0	0	0
Sunflowers	7	232	47	0
Oat	8	0	0	0
Peanuts	9	0	0	0
Soybeans	10	0	0	0
Rye	11	0	0	0
Cotton	12	9	2	0
Sorghum	13	2,136	429	0
Alfalfa	14	0	0	0
Corn	15	0	0	0
Wheat	16	3,662	735	0
Unknown irrigated crop	17	2,512	504	0
Irrigated soybeans	18	328	66	0
Irrigated peanuts	19	0	0	0
Cowpeas	20	0	0	0
Unknown crop	21	0	0	0
Irrigated alfalfa	22	0	0	0
Irrigated wheat	23	273	55	0
Hay/Pasture	24	2,293	460	0
Irrigated corn	25	994	200	0
Irrigated sorghum	26	5	1	0
Null	0	2,746,372	551,228	99
Image total		**2,781,751**	**558,329**	**100**

Appendix 4. Remote sensing classification categories shown with number of pixels and acres for the part of Gray County, Texas, in the Lake Altus drainage basin during the 2000 growing season

[Null, part of the image that is outside the portion of the drainage basin in the county]

Class name	Code	Pixels	Acres	Percent image
Urban	1	13,205	2,650	0
Water	2	31,256	6,273	1
Clouds	3	1,734	348	0
Fallow	4	89,254	17,914	3
Grass	5	1,761,917	353,637	59
Trees	6	43,566	8,744	1
Sunflowers	7	13,629	2,736	0
Oat	8	0	0	0
Peanuts	9	0	0	0
Soybeans	10	9,104	1,827	0
Rye	11	12,936	2,596	0
Cotton	12	3	1	0
Sorghum	13	37,820	7,591	1
Alfalfa	14	0	0	0
Corn	15	859	172	0
Wheat	16	143,573	28,817	5
Unknown irrigated crop	17	8,918	1,790	0
Irrigated soybeans	18	7,008	1,407	0
Irrigated peanuts	19	0	0	0
Cowpeas	20	0	0	0
Unknown crop	21	0	0	0
Irrigated alfalfa	22	934	187	0
Irrigated wheat	23	59,719	11,986	2
Hay/Pasture	24	99,635	19,998	3
Irrigated corn	25	13,910	2,792	0
Irrigated sorghum	26	743	149	0
Null	0	617,894	124,018	21
Image total		**2,967,617**	**595,634**	**100**

Appendix 5. Remote sensing classification categories shown with number of pixels and acres for the part of Greer County, Oklahoma, in the Lake Altus drainage basin during the 2000 growing season

[Null, part of the image that is outside the portion of the drainage basin in the county]

Class name	Code	Pixels	Acres	Percent image
Urban	1	487	98	0
Water	2	15,429	3,097	1
Clouds	3	0	0	0
Fallow	4	13,089	2,627	1
Grass	5	63,475	12,740	4
Trees	6	20,409	4,096	1
Sunflowers	7	0	0	0
Oat	8	29	6	0
Peanuts	9	2,504	503	0
Soybeans	10	0	0	0
Rye	11	1,257	252	0
Cotton	12	21	4	0
Sorghum	13	6	1	0
Alfalfa	14	12,847	2,579	1
Corn	15	0	0	0
Wheat	16	36,735	7,373	2
Unknown irrigated crop	17	4,764	956	0
Irrigated soybeans	18	0	0	0
Irrigated peanuts	19	1,119	225	0
Cowpeas	20	3,942	791	0
Unknown crop	21	4,906	985	0
Irrigated alfalfa	22	8,564	1,719	1
Irrigated wheat	23	2,985	599	0
Hay/Pasture	24	45,017	9,035	3
Irrigated corn	25	0	0	0
Irrigated sorghum	26	0	0	0
Null	0	1,454,766	291,988	86
Image total		**1,692,351**	**339,674**	**100**

Appendix 6. Remote sensing classification categories shown with number of pixels and acres for the part of Kiowa County, Oklahoma, in the Lake Altus drainage basin during the 2000 growing season

[Null, part of the image that is outside the portion of the drainage basin in the county]

Class name	Code	Pixels	Acres	Percent image
Urban	1	103	21	0
Water	2	15,089	3,029	3
Clouds	3	26	5	0
Fallow	4	8,592	1,725	1
Grass	5	33,530	6,730	6
Trees	6	11,653	2,339	2
Sunflowers	7	0	0	0
Oat	8	0	0	0
Peanuts	9	1,383	278	0
Soybeans	10	0	0	0
Rye	11	96	19	0
Cotton	12	384	77	0
Sorghum	13	4	1	0
Alfalfa	14	4,817	967	1
Corn	15	0	0	0
Wheat	16	53,878	10,814	9
Unknown irrigated crop	17	6,261	1,257	1
Irrigated soybeans	18	0	0	0
Irrigated peanuts	19	1,086	218	0
Cowpeas	20	2,803	563	0
Unknown crop	21	3,933	789	1
Irrigated alfalfa	22	3,443	691	1
Irrigated wheat	23	2,193	440	0
Hay/Pasture	24	12,069	2,422	2
Irrigated corn	25	0	0	0
Irrigated sorghum	26	0	0	0
Null	0	425,050	85,312	72
Image total		**586,393**	**117,696**	**100**

Appendix 7. Remote sensing classification categories shown with number of pixels and acres for the part of Potter County, Texas, in the Lake Altus drainage basin during the 2000 growing season

[Null, part of the image that is outside the portion of the drainage basin in the county]

Class name	Code	Pixels	Acres	Percent image
Urban	1	31,399	6,302	3
Water	2	2,738	550	0
Clouds	3	1,007	202	0
Fallow	4	36,225	7,271	3
Grass	5	52,846	10,607	4
Trees	6	25	5	0
Sunflowers	7	599	120	0
Oat	8	0	0	0
Peanuts	9	0	0	0
Soybeans	10	619	124	0
Rye	11	698	140	0
Cotton	12	6	1	0
Sorghum	13	5,127	1,029	0
Alfalfa	14	0	0	0
Corn	15	0	0	0
Wheat	16	39,696	7,967	3
Unknown irrigated crop	17	380	76	0
Irrigated soybeans	18	209	42	0
Irrigated peanuts	19	0	0	0
Cowpeas	20	0	0	0
Unknown crop	21	0	0	0
Irrigated alfalfa	22	5	1	0
Irrigated wheat	23	11,153	2,239	1
Hay/Pasture	24	17,034	3,419	1
Irrigated corn	25	5	1	0
Irrigated sorghum	26	37	7	0
Null	0	1,035,745	207,886	84
Image total		**1,235,553**	**247,990**	**100**

Appendix 8. Remote sensing classification categories shown with number of pixels and acres for the part of Roger Mills County, Oklahoma, in the Lake Altus drainage basin during the 2000 growing season

[Null, part of the image that is outside the portion of the drainage basin in the county]

Class name	Code	Pixels	Acres	Percent image
Urban	1	446	90	0
Water	2	2,372	476	0
Clouds	3	5	1	0
Fallow	4	46,842	9,402	2
Grass	5	267,012	53,592	13
Trees	6	21,000	4,215	1
Sunflowers	7	0	0	0
Oat	9	0	0	0
Peanuts	9	6,322	1,269	0
Soybeans	10	0	0	0
Rye	11	6	1	0
Cotton	12	2,436	489	0
Sorghum	13	8	2	0
Alfalfa	14	30,045	6,030	1
Corn	15	0	0	0
Wheat	16	35,067	7,038	2
Unknown irrigated crop	17	10,348	2,077	1
Irrigated soybeans	18	2	0	0
Irrigated peanuts	19	1,567	315	0
Cowpeas	20	326	65	0
Unknown crop	21	1,623	326	0
Irrigated alfalfa	22	9,978	2,003	0
Irrigated wheat	23	2,343	470	0
Hay/Pasture	24	34,260	6,876	2
Irrigated corn	25	0	0	0
Irrigated sorghum	26	0	0	0
Null	0	1,573,612	315,842	77
Image total		**2,045,620**	**410,579**	**100**

Appendix 9. Remote sensing classification categories shown with number of pixels and acres for the part of Washita County, Oklahoma, in the Lake Altus drainage basin during the 2000 growing season

[Null, part of the image that is outside the portion of the drainage basin in the county]

Class name	Code	Pixels	Acres	Percent image
Urban	1	0	0	0
Water	2	0	0	0
Clouds	3	0	0	0
Fallow	4	21	4	0
Grass	5	4,421	887	1
Trees	6	0	0	0
Sunflowers	7	0	0	0
Oat	8	2	0	0
Peanuts	9	474	95	0
Soybeans	10	0	0	0
Rye	11	2	0	0
Cotton	12	124	25	0
Sorghum	13	0	0	0
Alfalfa	14	115	23	0
Corn	15	0	0	0
Wheat	16	3,034	609	0
Unknown irrigated crop	17	190	38	0
Irrigated soybeans	18	0	0	0
Irrigated peanuts	19	57	11	0
Cowpeas	20	3,356	674	0
Unknown crop	21	4	1	0
Irrigated alfalfa	22	289	58	0
Irrigated wheat	23	49	10	0
Hay/Pasture	24	575	115	0
Irrigated corn	25	0	0	0
Irrigated sorghum	26	0	0	0
Null	0	809,145	162,405	98
Image total		**821,858**	**164,956**	**100**

Appendix 10. Remote sensing classification categories shown with number of pixels and acres for the part of Wheeler County, Texas, in the Lake Altus drainage basin during the 2000 growing season

[Null, part of the image that is outside the portion of the drainage basin in the county]

Class name	Code	Pixels	Acres	Percent image
Urban	1	16,772	3,366	1
Water	2	5,001	1,004	0
Clouds	3	49,108	9,857	2
Fallow	4	77,356	15,526	3
Grass	5	1,390,894	279,168	48
Trees	6	430,251	86,356	15
Sunflowers	7	94	19	0
Oat	8	4	1	0
Peanuts	9	5,195	1,043	0
Soybeans	10	8,107	1,627	0
Rye	11	2,144	430	0
Cotton	12	459	92	0
Sorghum	13	47,654	9,565	2
Alfalfa	14	35,649	7,155	1
Corn	15	132	26	0
Wheat	16	103,652	20,804	4
Unknown irrigated crop	17	26,993	5,418	1
Irrigated soybeans	18	4,795	962	0
Irrigated peanuts	19	3,221	646	0
Cowpeas	20	2,681	538	0
Unknown crop	21	8,827	1,772	0
Irrigated alfalfa	22	14,956	3,002	1
Irrigated wheat	23	23,653	4,747	1
Hay/Pasture	24	70,080	14,066	2
Irrigated corn	25	1,325	266	0
Irrigated sorghum	26	75	15	0
Null	0	577,827	115,976	20
Image total		**2,906,905**	**583,449**	**100**