USE OF LANDSAT THEMATIC MAPPER DATA TO IDENTIFY CROP TYPES AND ESTIMATE IRRIGATED ACREAGE, UVALDE AND MEDINA COUNTIES, TEXAS, 1991

By Lee H. Raymond and Scott I. McFarlane

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CONVERSION FACTORS

Multiply	By	To obtain
acre	0.4047	hectare
acre-foot	0.001233	cubic hectometer
inch	25.4	millimeter

Use of Landsat Thematic Mapper Data to Identify Crop Types and Estimate Irrigated Acreage, Uvalde and Medina Counties, Texas, 1991

By Lee H. Raymond *and* Scott I. McFarlane

Abstract

Landsat Thematic Mapper (TM) data were used to estimate that about 51,000 acres of crops were irrigated with water pumped from the Edwards aquifer in Uvalde and Medina Counties, Texas in 1991. Bands 2, 3, 4, and 5 from a TM image for August 10, 1991, were classified using the maximum-likelihood, unsupervised-classification procedure to identify the areas of crops irrigated in the two counties. Detailed vegetation distribution maps of two calibration sites in the study area, and boundaries of the areas probably irrigated in 1991, were used to interpret the results and to separate probable irrigated areas by county from the rest of the image.

Areas calculated for irrigated crops were 31,000 acres for Uvalde County, about 35 percent less than the area calculated using Landsat multispectral scanner (MSS) data in 1989, and 20,000 acres for Medina County, about 13 percent less than in 1989, a total decrease of about 28 percent for the two counties. Quantities of water pumped from the Edwards aquifer to irrigate crops in 1991 were estimated as 65,000 acre-feet for Uvalde County and 18,000 acre-feet for Medina County, a total decrease of about 56 percent from the value calculated using crop acreages from MSS data for 1989. Differences were attributed primarily to greater precipitation in 1991 than in 1989, resulting in smaller irrigation water requirements and less supplemental irrigation in 1991. Differences between results from 1989 and 1991, and between results from Uvalde and Medina Counties in 1991, were attributed primarily to greater precipitation in 1991, particularly in Medina County.

The total number of acres of irrigated crops estimated using Landsat TM data was about 9 percent lower in Uvalde County and about 13 percent lower in Medina County than the number of acres calculated from data reported by the U.S. Department of Agriculture, Agricultural Stabilization and Conservation Service (ASCS). The total quantity of water pumped from the Edwards aquifer for irrigation in the two counties in 1991, about 83,000 acre-feet, was about 5 percent greater than the quantity calculated from data reported by the ASCS.

INTRODUCTION

Annual estimates of the quantities and uses of water pumped from the Edwards aquifer in each county in south-central Texas are provided by the U.S. Geological Survey (USGS), in cooperation with the Edwards Underground Water District. The quantity of water pumped for irrigation of crops—about 24 percent of the total quantity pumped from the aquifer for all purposes in 1990 (Brown and others, 1991, table 4)—has been estimated from crop acreages provided by Federal, State, and local agencies, and from water application rates measured in some fields. Data on areas of irrigated crops necessary to make reliable estimates of pumpage for irrigation are difficult to obtain. A standardized, reproducible technique is needed to estimate the quantity of water pumped for irrigation.

Background

A recent study (Raymond and others, 1992) evaluated the use of Landsat multispectral scanner (MSS) data to identify crop types and estimate irrigated acreage in Uvalde and Medina Counties (fig. 1). Landsat MSS images for March and July 1989 were combined and classified, using techniques described in Raymond and Owen-Joyce (1987) and Raymond and Rezin (1989), to identify the areas of crops irrigated with water from the Edwards aquifer in the two counties. Results were compared with crop acreages reported by the U.S. Department of Agriculture, Agricultural Stabilization and Conservation Service (ASCS). The total areas for all irrigated crops estimated using Landsat MSS data were about 8 percent higher for Uvalde County and about 4 percent higher for Medina County than those reported by the ASCS.

Results of the classification using Landsat MSS data corresponded closely to those calculated using data reported by the ASCS primarily because digitized boundaries were used to isolate areas of the classified image that probably were irrigated in 1989. Thus, the total area of irrigated crops was similar to that reported by the ASCS. Differences between acreages of individual crops estimated from Landsat MSS data and those reported by the ASCS were as high as almost 50 percent (Raymond and others, 1992, table 3). These differences, however, tended to offset each other when the total irrigated-crop areas were similar.

The two Landsat MSS images used for the 1989 classification did not contain sufficient information to distinguish among some types of vegetation. For example, irrigated and nonirrigated corn and milo and noncultivated grasses were grouped into a single class in the classification (Raymond and others, 1992, p. 23). Only by digitally separating the probable irrigated areas from the rest of the classified image could the acreage of irrigated corn be distinguished partly from the other vegetation types and from nonirrigated corn.

On the basis of results presented in Raymond and others (1992), a second study was begun to evaluate the use of Landsat Thematic Mapper (TM) data to identify crop types and estimate irrigated acreage. The increased spatial resolution of the TM data (approximately four times greater than that of the MSS data) and additional spectral bands permit potentially better discrimination of vegetation types from each other and from other types of ground cover.

Purpose and Scope

This report describes the technique that was developed to identify and estimate areas of irrigated crops using Landsat TM data for 1991, in Uvalde and Medina Counties, Texas. Irrigated-crop acreages were used to estimate the quantity of water pumped in 1991 from the Edwards aquifer in the two counties.

Acknowledgment

The authors express their appreciation to the U.S. Department of Agriculture, Agricultural Stabilization and Conservation Service for providing records of irrigated-crop areas for 1991 in Uvalde and Medina Counties.

CROP IDENTIFICATION BY CLASSIFICATION OF LANDSAT THEMATIC MAPPER DATA

Remote-sensing data, particularly aerial photographs, have been used to identify and map areas of vegetation for many years. Remote-sensing data from satellites became widely available with the initiation of the Landsat program in 1972. The combination of standardized, scale-stable digital images and large-capacity, high-speed digital computers has revolutionized vegetation classification and mapping techniques.

In 1982, Landsat 4 began transmitting images acquired by the TM scanner. Techniques using Landsat TM data have been developed to classify vegetation types in various parts of the world. The techniques differ because climate, vegetation types, and local growing conditions differ. The following sections include descriptions of the classification techniques used in this study in south-central Texas and of the methods used for crop identification and calibration of the classified images from Landsat TM data.

Definitions of the procedures described in the following sections are as follows:

1. **Classification technique**—classification of digital Landsat TM data to yield spectral classes.
2. **Collection of calibration data**—preparation of calibration data sets by identifying vegetation types on the ground in calibration areas.
3. **Interpretation of the classification**—assignment of spectral classes to ground-cover types using calibration data sets.

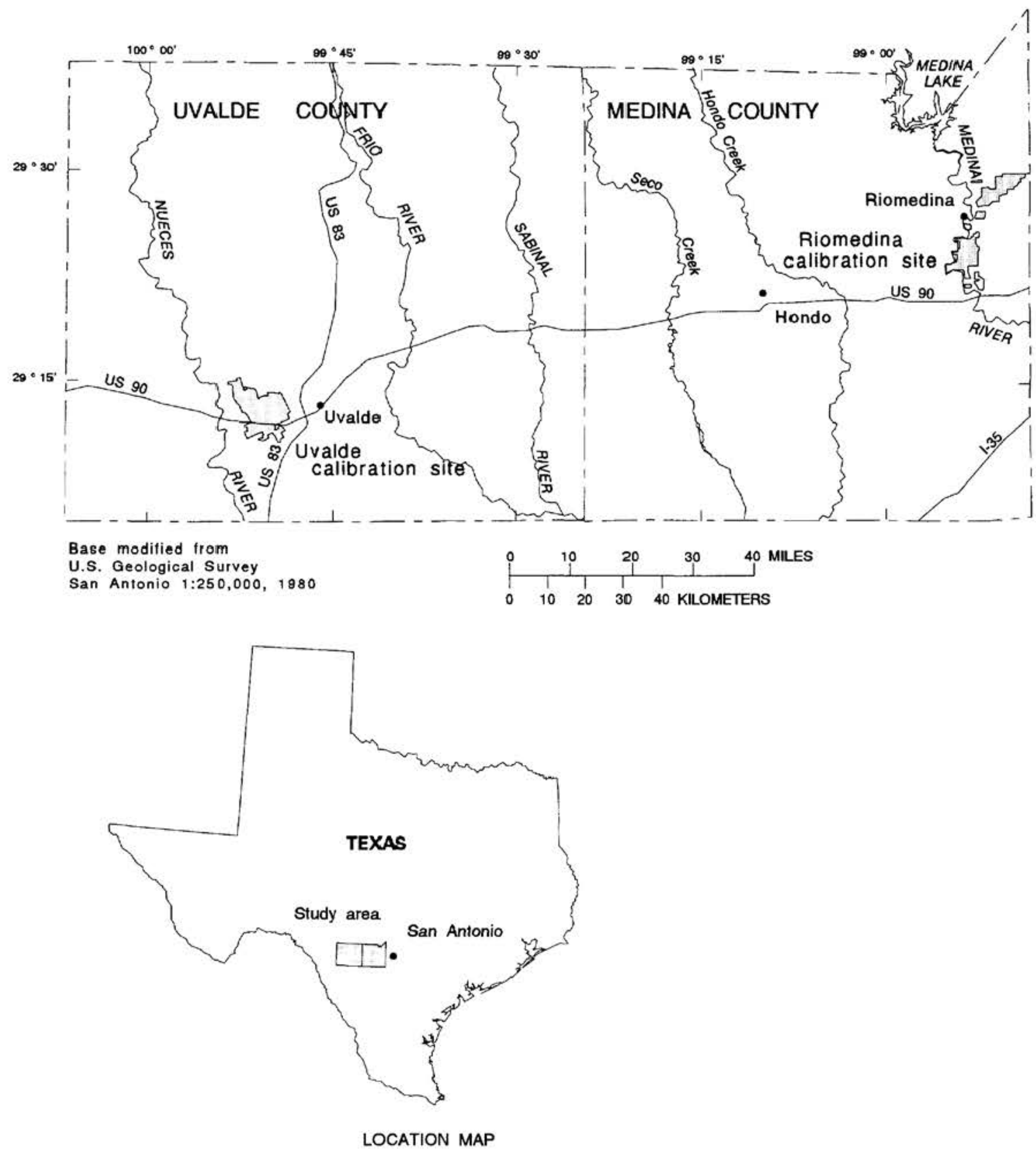


Figure 1. Location of study area and calibration sites.

4. **Estimation of crop acreage**—determination of irrigated-crop areas using areas of ground-cover types and ancillary data, including the boundaries of probable irrigated areas.

The computer software used for the following analysis was ELAS (Earth Resources Laboratory Applications Software), a nonproprietary image-analysis package developed by the Earth Resources Laboratory of the National Aeronautics and Space Administration. The reader is referred to the software manual (Beverly and Penton, 1989) for a more detailed technical description of the image-processing techniques than this report provides. The geographic information system ARC/INFO (Environmental Systems Research Institute, 1987) also was used to augment parts of the analysis and to prepare some of the illustrations for this report.

Description of the Classification Technique

Images are collected by Landsats 4 and 5 alternately at 8-day intervals over any particular area of the earth. Weather conditions, technical problems with image acquisition by the satellites, and priority scheduling of image acquisitions further limit the number of usable images available over a particular area during a given time period. Therefore, images might not be available during the parts of the growing season most favorable for mapping a particular vegetation type in any given year.

Acquisition of usable images for the study area was particularly difficult in 1991. Greater precipitation in 1991 than in 1989 resulted in fewer cloud-free images available for 1991 than for the 1989 study (Raymond and others, 1992). (A cloud-free image was defined as an image with 10 percent or less cloud cover over the study area.) Two cloud-free images were acquired during the 1991 growing season, but one image had electronic noise and could not be used. The only usable TM image of the study area during the 1991 growing season was acquired on August 10.

The Landsat TM scans the ground as the satellite passes over it and records electromagnetic reflectance in seven bands of the electromagnetic spectrum: band 1 (0.45 to 0.52 μm (micrometer)), band 2 (0.52 to 0.60 μm), band 3 (0.63 to 0.69 μm), band 4 (0.76 to 0.90 μm), band 5 (1.55 to 1.75 μm), band 6 (10.40 to 12.50 μm), and band 7 (2.08 to 2.35 μm). Band 6 records thermal infrared reflectance values that were not used in the classification and will not be discussed further in this report. Each scan line is composed of pixels, with each pixel containing the average reflectance of a land-surface area 30 by 30 meters (approximately 0.22 acre). The electromagnetic reflectance of each pixel received by the TM sensor is converted to a dimensionless digital number and then relayed to a receiving station on the ground. Each number corresponds to the average reflectance for one pixel in one of the spectral bands, ranging from 0 (black, or no reflectance) to 255 (white, or total reflectance).

Georeferencing is the process of correcting scanned images for the curvature of the earth, distortions from the scanner, and flight path of the satellites to establish the geographic location of each pixel in an image. Georeferencing is required when images are to be combined with each other prior to classification or combined with other spatial-data layers such as county boundaries. Ground-control points, such as road intersections, were identified on a video display of the digital images, and the row and column numbers of the corresponding pixels were determined. The UTM (Universal Transverse Mercator) coordinates for each of these points were digitized from USGS 7-1/2-minute quadrangles using ARC/INFO. The file of UTM coordinates then was imported into ELAS. A georeferencing program in ELAS (Beverly and Penton, 1989, p. GRPOLY1, GRDMAP1) was used to build a transformation fit of the row and column numbers of the ground-control pixels to their UTM coordinates from the maps. The program then remapped the images to UTM coordinates using the transformation calculated during the fitting process. The resulting raster array consisted of pixels, each covering 0.22 acre and coded for geographic location on the UTM grid.

Normalized difference, used by Raymond and others (1992), is an information extraction technique designed to digitally enhance the vegetation information in an image while reducing the total volume of data. The technique is used for multispectral, multitemporal image classifications where the volume of raw data is too large and complex for direct classification. The single 1991 image contained vegetation information only for vegetation growing on August 10. Some irrigated crops, including corn and milo, usually have been harvested before August in the study area. Spectral reflectance from nonvegetated surfaces, such as stubble and bare soil in the harvested fields of corn, milo, and other early summer crops, was important to obtain the best classification possible using a single image. Therefore, normalized difference was not calculated prior to the classification of the August 10, 1991, image.

The volume of raw data in the August 10 TM image was reduced prior to classification by selecting bands 2, 3, 4, and 5. These bands were selected because they contain most of the data available to distinguish vegetation from nonvegetation types of ground cover in the image, to distinguish vegetation types from each other, and to discriminate bare soil characteristics. Bands 2, 3, and 4 cover approximately the same spectral range (0.52 to 0.90 μm) as do the four MSS bands (0.40 to 1.1 μm). Band 2 is useful for assessing plant vigor, band 3 contains information for discriminating vegetation types, and band 4 is useful for determining biomass content. Band 5 (no MSS equivalent) indicates moisture content of soil and vegetation and gives good contrast between vegetation types (Sabins, 1987, p. 86).

Bands 2, 3, 4, and 5 were classified using a maximum-likelihood, unsupervised-classification procedure. The ELAS subprogram SRCH (Beverly and Penton, 1989, p. 9-21, 9-22) automatically collected homogeneous training samples from the unclassified image and recorded this information in a statistics subfile. For this classification, a digital number scaled distance value of 3.0 (the default value) was used as the threshold to discriminate between similar and dissimilar reflectance characteristics in the four spectral bands. A class number was assigned by SRCH to each set of statistics that defined a class. The subprogram CLMAXL (Beverly and Penton, 1989, p. 9-23) was used to assign each input pixel to the number of the class with the most similar reflectance characteristics. The output was a single image channel with the value of each pixel replaced by its spectral class.

Calibration of the Classification

A necessary assumption made for image classification is that all of the pixels in each class represent the same type of ground cover and that different classes represent different types of ground cover, including different types of vegetation. This is rarely, if ever, the case. Two or more classes could contain the same type of ground cover, such as alfalfa at different stages of growth after mowing, or bare soils with different structures or soil-moisture conditions. Conversely, different types of ground cover, such as corn and various noncultivated grasses, could have the same spectral characteristics on the particular image date selected and thus might be grouped into the same ground-cover class. Also, spectral characteristics of a particular ground-cover class are not unique to the type of ground cover represented. The characteristics vary with time of image acquisition, atmospheric conditions, soil moisture, and other variables. One type of ground cover might form more than one ground-cover class. Therefore, classifications require calibration and interpretation in one or more locations where the ground cover is known.

Collection of Calibration Data

Calibration sites were selected on the basis of the following criteria: (1) the crop mix at each of the calibration sites was representative of the larger area being classified; (2) the proportion of crops in the calibration sites was typical of the larger area; (3) fields of uniform crop cover were as large as possible to minimize the effects of roads and other border conditions in the corresponding part of the classified image; (4) nonirrigated crops and noncultivated vegetation were well represented; and (5) the calibration sites were reasonably easy to access on the ground. The calibration sites near the towns of Uvalde and Riomedina (fig. 1) also were used as calibration sites in a previous study by Raymond and others (1992). Vegetation distribution at the two calibration sites was field mapped in July 1991 to identify specific vegetation types in the classification. The vegetation distribution, particularly crop distribution, in July usually persists into early August, although the appearance of the vegetation from a vertical perspective could change as it matures or as crops are harvested.

A common problem in mapping vegetation at the calibration sites was the difficulty of determining field size, shape, and precise location from a ground-level perspective. Boundaries of cultivated fields were determined from 7-1/2-minute quadrangles by using roads and other map features. The boundaries were updated by using color infrared aerial photographs of the study area taken in 1989. The photographs, taken at an approximate scale of 1:32,000, clearly showed the boundaries of cultivated fields.

Field boundaries that were apparent on the 1989 aerial photographs, however, did not always correspond to the perimeters of cropped areas on the ground in 1991. Two or more fields, as determined from the maps or photos, occasionally were planted with the same crop, obliterating any boundaries between the fields. Some large fields, as determined on the maps, were planted with two or more areas of different crops that appeared to be separate fields at ground level. Discrepancies between the maps and actual field conditions resulted in some disorientation in the field. Therefore, some crops were mapped in the wrong fields. Disorientation also occurred from time to time during the mapping process as a result of driving on small, unmarked dirt roads in unfamiliar territory. Therefore, some inaccuracies in the vegetation distribution maps were inevitable.

Uvalde Calibration Site

The Uvalde calibration site is in the southwestern part of the study area (fig. 1) in Uvalde County. The detailed vegetation distribution map (fig. 2A) includes about 5,000 acres of vegetation. A slightly different distribution of fields was mapped in 1991 than in 1989 (Raymond and others, 1992, fig. 2) to provide a more representative mix of vegetation types for the calibration. The fields were large, with a relatively large proportion of corn and cotton (the principal irrigated crops). Fallow fields (bare soil) also covered fairly large areas. Stubble was identified as corn, milo, or fallow fields. A few fields of milo, cane, pasture, or vegetables were identified. The remainder of the mapped vegetated area was covered with brush or grasses.

Fields of cotton, cane, pasture, and vegetables each appeared to have a dense, uniform distribution; the plants were medium to dark green. Most of the corn and milo had been harvested and only dead plants or stubble remained in those fields. Corn density, where plants remained standing, was variable, with sparsely covered or bare spots apparent in many fields. In some fields, stubble already had been plowed under and was difficult to identify; these fields usually were mapped as bare soil. Some fields in the calibration site were not mapped because they were inaccessible.

Riomedina Calibration Site

The Riomedina calibration site is in the northeastern part of the study area (fig. 1) in Medina County. A detailed vegetation distribution map was prepared (fig. 3A) and included about 5,400 acres of vegetation. Corn and milo were the most common crop types. Several fields of cotton were mapped. A few fields each of cane, pasture, and alfalfa also were mapped. Many more fields of stubble were mapped than at the Uvalde calibration site. Crop types could not be determined for fields identified as stubble or bare soil on the vegetation distribution map. Noncultivated grasses were not evident in fields at the Riomedina calibration site.

The area of the Riomedina calibration site used for the 1989 study (Raymond and others, 1992, fig. 3), essentially the area south of Riomedina (fig. 1), did not include enough large, cropped fields for a good calibration of the image classification in this part of the study area. Many of the fields of crops were close to or on the Medina River flood plain. The plants might have had their roots in the saturated zone and were using ground water associated with the river. The area north of Riomedina that was added to the calibration site in 1991 included large fields of corn, milo, and cotton. Most of the fields in the additional area were located farther away from the Medina River flood plain.

Interpretation of the Classification

Interpretation of the image classification was made using the classification results and the two vegetation distribution maps. Spectral classes were identified throughout the study area by matching fields on the image to fields on the vegetation map. The entire spectral class then was identified as the vegetation type represented by the field pairs. Some classes were so small or discontinuous that they were not represented in the vegetation maps. Field observations by personnel working in the study area were used whenever possible to help identify these classes. Most were identified as nonirrigated or noncultivated vegetation. In cases where two or more vegetation types had the same characteristics and thus were combined into the same spectral class, the predominant vegetation type was selected because it had the greatest probability of being correct. Therefore, several vegetation types with relatively small areas in the calibration sites were misidentified as vegetation types that had larger areas in the calibration sites.

Chlorophyll absorbs red radiation in the 0.63 to 0.69-μm range (band 3 in the TM image) and reflects infrared radiation in the 0.76 to 0.90-μm range (band 4). Water, soil, rocks, and other nonvegetated ground cover typically absorb or reflect about the same quantity of radiation in both bands. This characteristic spectral response of vegetation compared with that of nonvegetation was used to help distinguish vegetation growing in August from other types of ground cover in the image.

Classification of the August 10, 1991, image yielded 49 spectral classes. Of these, 23 represented vegetation, as interpreted from the average reflectance values in bands 3 and 4 and the vegetation distribution maps for the calibration sites, or fields where vegetation had been growing earlier in the year. Each ground-cover type typically forms several spectral classes because of variations in spectral response among areas of that type. Corn and milo were not growing in the fields at the time of the overpass. The stubble in the harvested fields had spectral responses that were distinctive from the other nonvegetated surfaces, and the vegetation maps were used to assign crop types to stubble spectral classes. After each vegetation ground-cover class was identified, classes of the same vegetation type were combined to form principal ground-cover types containing all classes of that vegetation type.

Several ground-cover classes included fields of two or more vegetation types. Noncultivated grasses frequently were included in ground-cover classes with corn or milo fields. Some of the corn or milo stubble appeared quite similar to sparse, dry grasses in August, which typically is the hottest, driest month of the year in south-central Texas. Classes that contained a mixture of corn and grasses or milo and grasses were determined to be nonirrigated because of the sparse and uneven distribution of plants or stubble and the fact that the grasses were not irrigated. Classes that contained only corn stubble were determined to be irrigated corn because of the relatively uniform distribution of stubble cover. The distinction between these classes was substantially arbitrary because it could be based only on the distribution characteristics of dead plants. There were no classes that contained only milo.

Spectral classes that contained corn, cotton, and milo fields also contained the few cane, pasture, alfalfa, and vegetable fields mapped in the calibration sites. These crops could not be separated from each other using a single image date because all of these crops had a uniformly dense and even ground cover on August 10. On the basis of results presented in Raymond and Rezin (1989), an additional image characterizing the early part of the growing season might have provided enough data to separate these crop types in a multispectral, multitemporal classification. Five ground-cover types were identified for the vegetated areas of the calibration sites: irrigated corn, nonirrigated corn and grasses, cotton, nonirrigated milo and grasses, and brush.

The remaining ground-cover classes included all nonvegetated surfaces that had not been identified as corn or milo. The predominant ground-cover type was bare soil. Other nonvegetated ground-cover types included a few clouds and cloud shadows, asphalt and other synthetic materials, and water. All but a few pixels of these ground-cover types, other than bare soil, were outside the calibration sites. The nonvegetated ground-cover classes were combined into a single principal ground-cover type identified as bare soil.

Classification results for the Uvalde calibration site are shown in figure 2B. Cotton distribution in the classified image closely corresponded to cotton distribution mapped at this site (fig. 2A). Areas classified as irrigated and nonirrigated corn and milo were less distinct when compared to the mapped vegetation distribution because these crops were classified on the basis of stubble and bare soil characteristics. Classification results for the Riomedina calibration site are shown in figure 3B. Cotton distribution in the classified image corresponded more closely to mapped cotton distribution (fig. 3A) than did any other classified ground-cover type to the corresponding mapped area at the Riomedina calibration site.

Some specific discrepancies between the vegetation distribution maps and the principal ground-cover types from the classification at the calibration sites are evident. For example, the locations of some field boundaries on the vegetation distribution maps do not correspond exactly to field boundaries on the corresponding classified image. These discrepancies probably are related to errors in determining the exact location of the boundaries of uniform cropped areas during the vegetation mapping. Alfalfa fields in the southern part of the Riomedina calibration site were classified as cotton. Two of these fields, in the southwestern corner of the site, appeared circular on the classified image (indicating that they had received center pivot irrigation in 1991), but were mapped as a single, irregularly shaped field. This illustrates the problems of determining field boundaries correctly on the ground, and of misclassifying some minor vegetation types.

Many fields mapped as stubble, particularly between the Medina River and FM 471 at the Riomedina calibration site, were classified as nonirrigated corn and grasses or as nonirrigated milo and grasses. These fields might or might not have been irrigated in 1991. An apparent boundary (fig. 3B) between irrigated corn and nonirrigated corn and grasses, just west of FM 471 and generally parallel to it in the southern

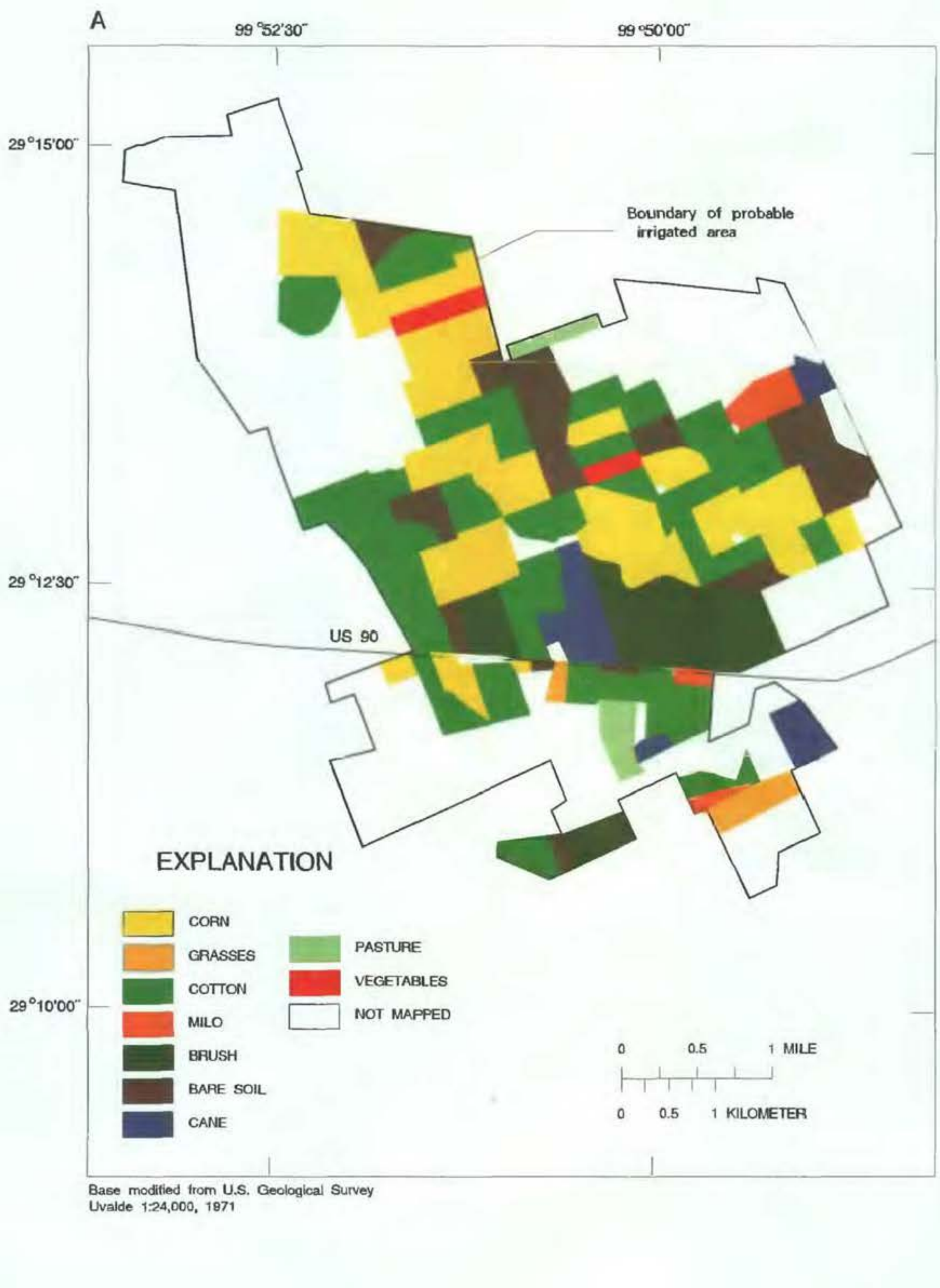
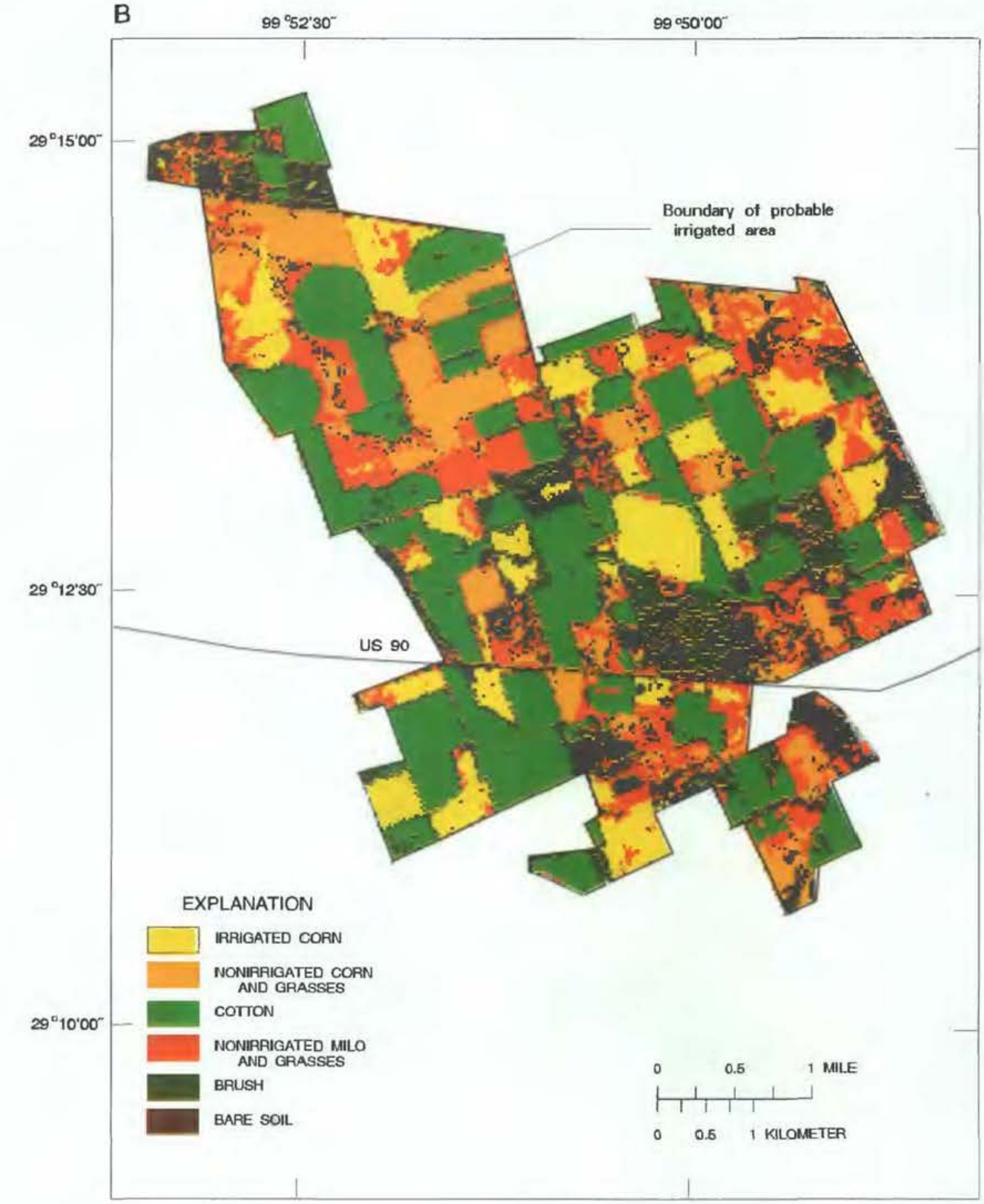


Figure 2. Vegetation distribution (A) and classified image (B) for a probable irrigated area at the Uvalde, Texas, calibration site, 1991.


B
99°52'30"
99°50'00"
29°15'00"
29°12'30"
29°10'00"
Boundary of probable irrigated area
US 90
EXPLANATION
IRRIGATED CORN
NONIRRIGATED CORN AND GRASSES
COTTON
NONIRRIGATED MILO AND GRASSES
BRUSH
BARE SOIL
0 0.5 1 MILE
0 0.5 1 KILOMETER

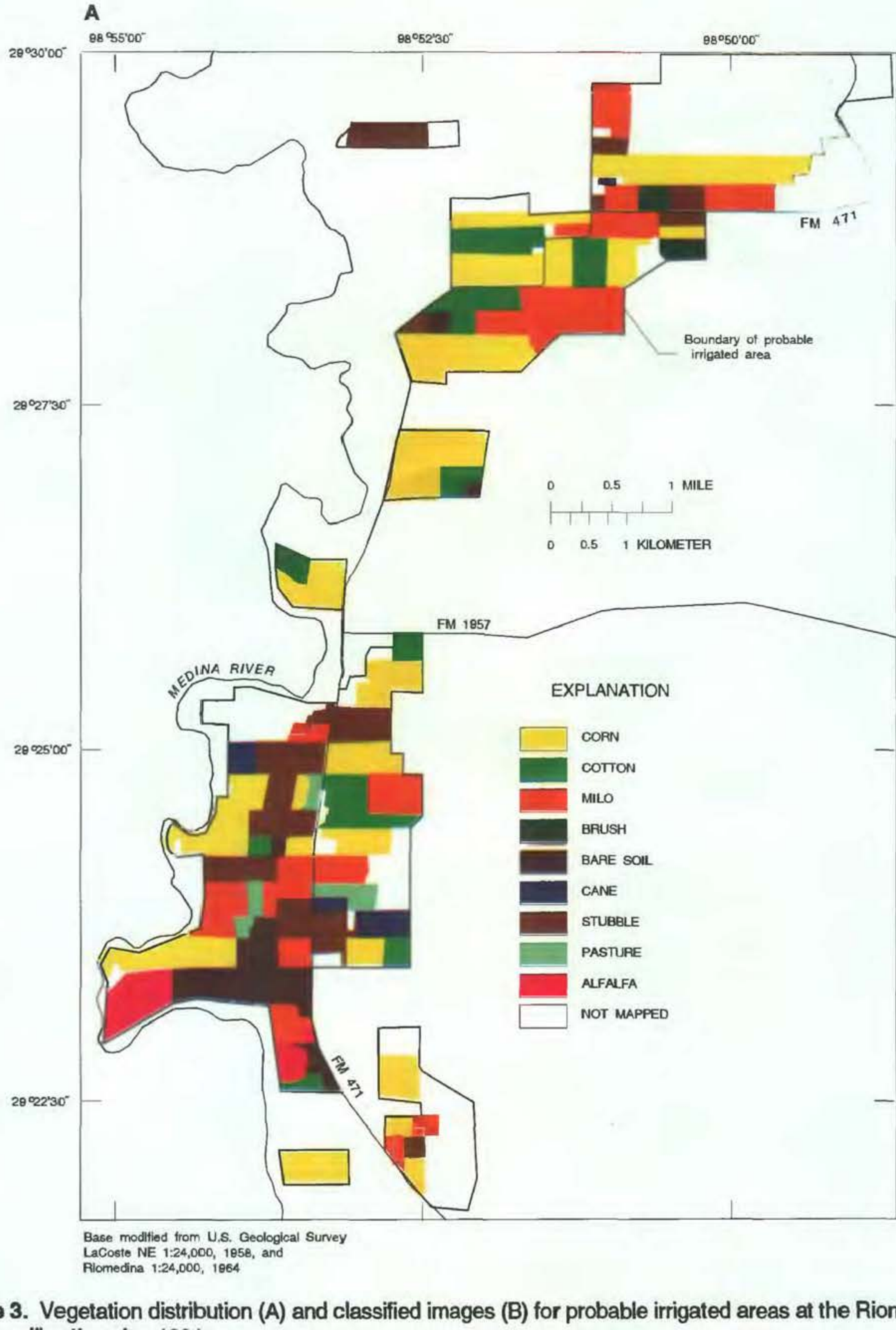
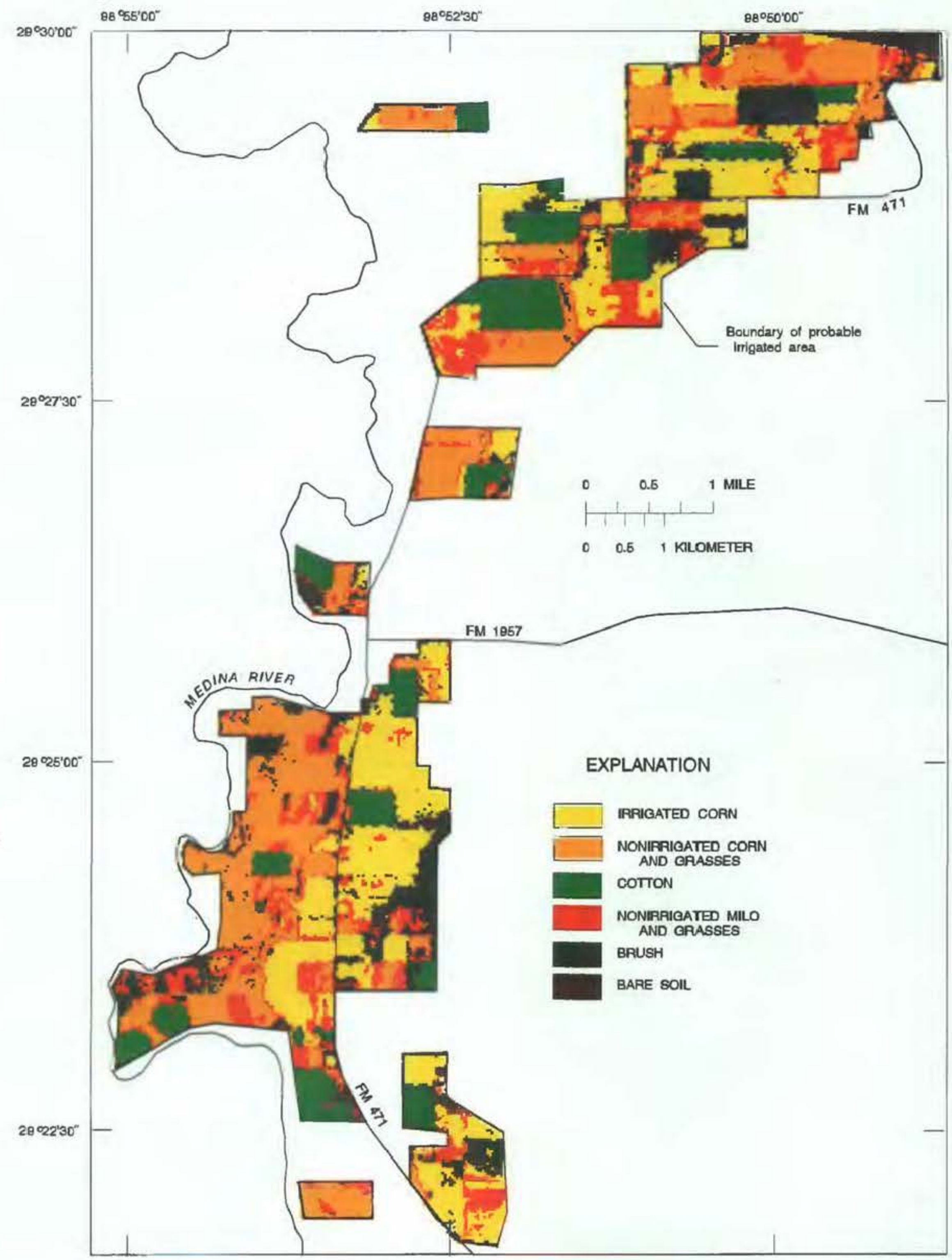


Figure 3. Vegetation distribution (A) and classified images (B) for probable irrigated areas at the Riomedina, Texas, calibration site, 1991.

B


98°55'00"
98°52'30"
98°50'00"
29°30'00"
29°27'30"
29°25'00"
29°22'30"
FM 471
Boundary of probable irrigated area
0 0.5 1 MILE
0 0.5 1 KILOMETER
FM 1957
MEDINA RIVER
EXPLANATION
IRRIGATED CORN
NONIRRIGATED CORN AND GRASSES
COTTON
NONIRRIGATED MILO AND GRASSES
BRUSH
BARE SOIL
FM 471

part of the image, results from different spectral characteristics of the soil and stubble on either side of the boundary. This spectral difference probably is related to differences in soil moisture or soil texture as well as to differences in characteristics of the stubble. If so, the spectral difference could indicate the boundary of the flood plain in this part of the study area. Although the boundary of the Medina River flood plain was not established for this study, the spectral difference apparent on the classified image is in the vicinity of the edges of the flood terraces noted but not recorded during the vegetation mapping.

In the 1989 classification of Landsat MSS images (Raymond and others, 1992), irrigated and nonirrigated corn and milo and noncultivated grasses all were classified into a single ground-cover class and identified as corn, the predominant crop, because of insufficient differences in spectral response at MSS resolution. In the 1991 classification of TM images, some separation of irrigated corn, nonirrigated corn and grasses, and nonirrigated milo and grasses is evident in the calibration sites (figs. 2B and 3B). The separation could be caused partly by differences in soil moisture content. Substantial areas of these ground-cover types, however, appear outside the parts of the study area where crops are irrigated with water from the Edwards aquifer. A direct count of the pixels for each of the ground-cover types also included areas known to be irrigated with water from other than the Edwards aquifer and areas known not to be irrigated. Subdivision of the classified image, discussed in the next section, was required to isolate areas irrigated with water from the Edwards aquifer.

ESTIMATION OF IRRIGATED-CROP ACREAGE

The areas most likely to contain irrigated crops were identified by county and then separated from the rest of the study area in the classified image. The technique described here for identifying and digitizing boundaries and merging them with the classified image to calculate areas of irrigated crops combined ELAS procedures with those of ARC/INFO.

Identification and Separation of Probable Irrigated Areas

The classified image alone did not include enough information to define the boundaries of the irrigated fields. The 7-1/2-minute quadrangles were used as a source of field boundaries because they contained the most detailed and uniform coverage of the entire study area. Many field boundaries are indicated on the maps—but only those that existed when each of the maps was made. Many of those fields in the proximity of mapped water wells probably have been irrigated at least part of the time. Fields can be irrigated fully, as a supplement to rainfall, or not at all in any given year, depending on local weather conditions and on individual farming practices. The location and boundaries of areas where irrigation was most probable in 1989 were determined for the study described in Raymond and others (1992) by comparing the maps with (1) records of well inventories (U.S. Geological Survey, unpublished data) conducted in the study area since the topographic maps were made; (2) unpublished data from the U.S. Department of Agriculture, Soil Conservation Service; and (3) field observations. These areas (hereafter referred to as probable irrigated areas) contained not only the irrigated fields, but also some nonirrigated and noncultivated vegetation.

Boundaries of probable irrigated areas were updated from the 1989 aerial photographs. However, irrigated fields could not be distinguished definitively from nonirrigated fields on the photographs. Some fields of dense, uniform vegetation probably were irrigated, and some fields of sparse, unevenly distributed vegetation probably were not irrigated. Most fields appeared to have vegetation cover that was intermediate between these two extremes. Many fields that appeared fallow on the photographs might have had irrigated or nonirrigated crops at other times during the growing season or during other years. Also, as discussed previously, any field served by an irrigation system can be fully irrigated, partly irrigated, or not irrigated at all during any given year.

The photographs did provide more definitive and recent boundaries for probable irrigated areas than those interpreted by Raymond and others (1992). Boundaries of probable irrigated areas identified on the photographs were drafted onto the 7-1/2-minute quadrangles and digitized into ARC/INFO. Adjacent polygons of the same probable irrigated area on two or more quadrangles were merged into a single polygon for that area, and polygons were divided by counties. The boundaries of the probable irrigated areas for Uvalde and Medina Counties are shown in figures 4 and 5, respectively.

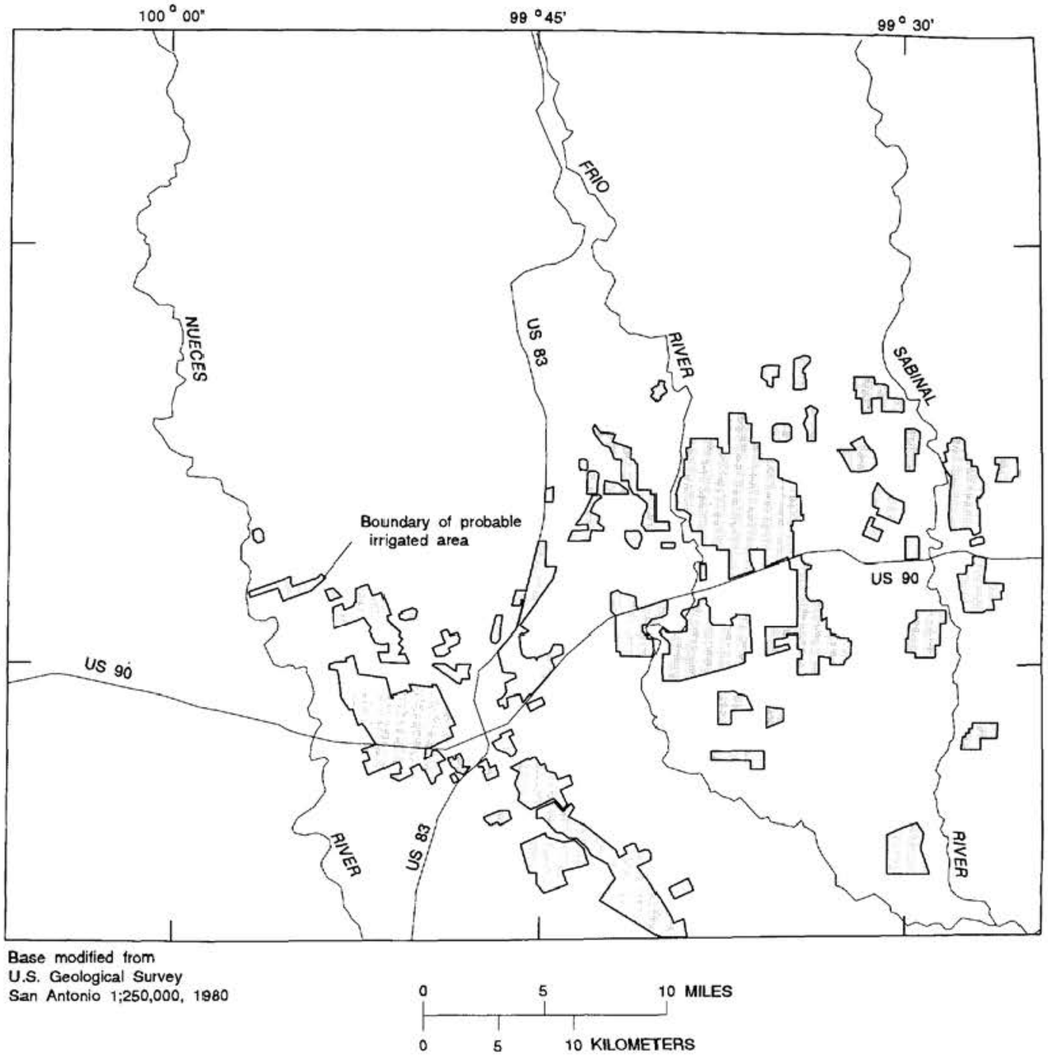


Figure 4. Boundaries of probable irrigated areas in Uvalde County, Texas, 1991.

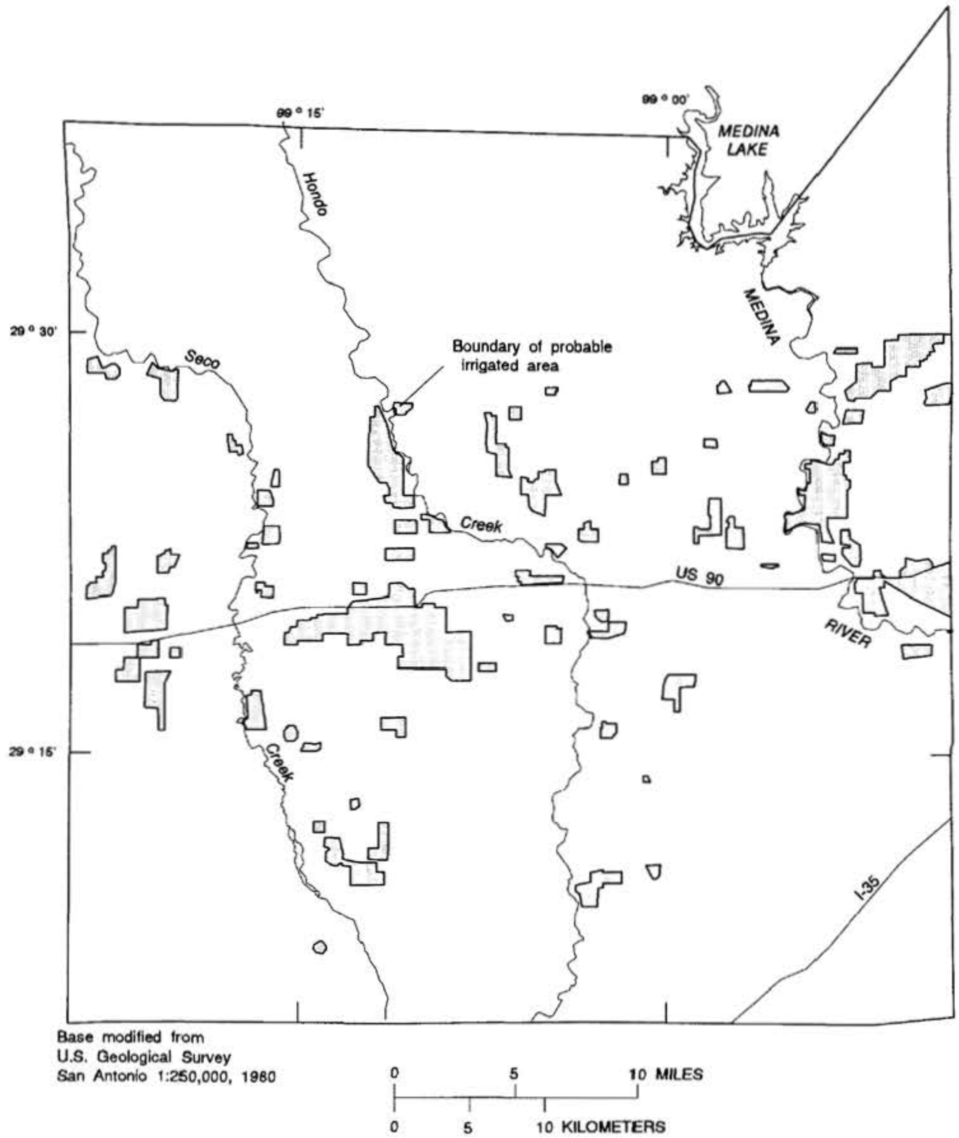


Figure 5. Boundaries of probable irrigated areas in Medina County, Texas, 1991.

The polygon data in ARC/INFO were converted to UTM coordinates and subsequently transferred into ELAS as a polygon file. The parts of the classified image that were within the boundaries of the probable irrigated area polygons were separated from the rest of the image. The boundaries of the probable irrigated areas at the Uvalde and Riomedina calibration sites are shown in figures 2 and 3.

Determination of Acreages

The number of acres covered by each principal ground-cover type in the probable irrigated areas was calculated as follows: (1) the number of pixels in each class was summed; and (2) the sums were multiplied by 0.22 acre per pixel. Results are listed in table 1.

The probable irrigated areas in Uvalde County included larger acreages of all principal ground-cover types, except brush, than did those in Medina County. The area of irrigated crops calculated for Uvalde County in the present study was 31,000 acres, about 35 percent less than the area calculated by Raymond and others (1992) for the 1989 classification. For Medina County, the area of irrigated crops calculated in the present study was 20,000 acres, about 13 percent less than in the previous study. Part of the difference between the acreages of irrigated crops calculated for 1989 and 1991 can be explained by greater precipitation in 1991 than in 1989 (Brown and others, 1992, table 1), resulting in smaller areas of irrigated crops in 1991, or by differences between acreages of the crops planted. Part of the difference also resulted from refinement of the boundaries of the probable irrigated areas determined from the aerial photographs. Differences in the classification techniques using Landsat TM and MSS data undoubtedly also contributed to differences in the areas of irrigated crops.

Comparison of Reported and Estimated Acreages

Data on areas of irrigated crops in Uvalde and Medina Counties for 1991 were obtained from ASCS records. The total of each crop type was increased by 11 percent to compensate for areas of crops not enrolled in government subsidy programs and therefore not reported (G.M. Nalley, U.S. Geological Survey, oral commun., 1992). The 11 percent was an overall estimate and might not be exact for each crop type. Areas of crops reported from parts of the study area known to be irrigated with surface water were subtracted from the totals. The areas of irrigated crops estimated by the USGS from the classification of Landsat TM data along with the adjusted areas of crops irrigated with water from the Edwards aquifer as reported by the ASCS are listed in table 2.

The total number of acres of irrigated crops estimated by the USGS using Landsat TM data was about 9 percent lower in Uvalde County and about 13 percent lower in Medina County than the adjusted number of acres reported by the ASCS. Probable causes of the discrepancies include the following: (1) errors in adjusting the ASCS numbers for factors discussed previously; (2) inclusion of some irrigated corn and milo in the nonirrigated ground-cover types; and (3) errors in identifying the number and size of probable irrigated areas.

Some differences between the two estimates of crop acreages also might be attributed to differences in the ways in which the acreages of crops are determined. Landsat data include reflectance values of the ground cover of the crop within the vegetated area; 38 acres planted with cotton might include 35 acres of uniformly dense cotton plants and 3 acres of sparse plant cover or bare soil. In this case, Landsat would record 35 acres of pixels with the reflectance characteristics of cotton and 3 acres with the reflectance characteristics of fallow fields or grasses. The ASCS calculates crop areas based on field size—excluding roads and other nonvegetated surfaces; a 40-acre field with 38 acres planted with cotton is reported as 38 acres of cotton.

CALCULATION OF THE QUANTITY OF IRRIGATION WATER PUMPED

The quantities of irrigation water applied to cultivated fields vary widely, even within a relatively small area with consistent agricultural practices. Principal causes of the variations include crop type, season of the year, soil type, variations in solar radiation and quantities of precipitation from year to year, variations in farming practices between individual farmers, and other related factors. Rarely, if ever, are the data available to determine the effects of all these factors, except in carefully controlled research projects. In most situations, the quantity of water applied to crop areas is calculated using data readily available.

The duty of water was defined in this study as the average quantity of water applied to a given crop type

Table 1. Areas of principal ground-cover types in the probable irrigated areas of Uvalde and Medina Counties, Texas, 1991

[in acres; values are rounded to two significant figures]

Class number	Ground-cover type	Uvalde County	Medina County	Total area
1	Irrigated corn	14,000	9,700	24,000
2	Nonirrigated corn and grasses	11,000	7,300	18,000
3	Cotton	17,000	10,000	27,000
4	Nonirrigated milo and grasses	17,000	8,000	25,000
5	Brush	3,100	3,800	6,900
6	Bare soil	12,000	5,400	17,000
	Total	74,000	44,000	120,000

over the lifespan of the crop. The duties of water for crops in Uvalde and Medina Counties in 1991 were calculated for this study using individual fields of representative crops, and subsequently averaged by county (P.L. Rettman, U.S. Geological Survey, written commun., 1992). The variables used to calculate the duty of water for each field were well yield, well operating time, and the area of the field. A few wells had water volume totalizing meters installed; in these cases, the area of the field was the only additional variable required. In the remaining cases, the well yield was measured on site, and well operating time was computed from energy meters or from a clock activated by the pump. Occasionally, well operating time was reported by the farmer. Areas of the individual fields were obtained from farm records or from field measurements. The average duty of water calculated from these data for each irrigated-crop type in Uvalde and Medina Counties in 1991 is listed in table 2.

The duties of water calculated for 1991 averaged about 30 percent less than those calculated for 1989 in Uvalde County and about 54 percent less in Medina County. The duties of water calculated for Medina County in 1991 also were substantially less (more than 50 percent less in most cases) than those calculated for Uvalde County. Most of these differences probably result from greater precipitation in 1991 than in 1989 and from the spatial variability of precipitation in 1991 (Brown and others, 1992, table 1). Farmers in that part of Texas who irrigate their fields use irrigation as a supplement to precipitation. In a wet year, the duty of water applied to a crop can be substantially less than the duty applied in a dry year or even in an average year. If precipitation consistently is greater than average during the growing season, the crop could receive no supplemental irrigation. Annual precipitation in 1991 recorded at the city of Uvalde (Uvalde County) was 21.77 inches compared to 18.65 inches in 1989. In Hondo (Medina County), annual precipitation in 1991 was 34.54 inches compared to 16.10 inches in 1989 (Brown and others, 1992, table 1). Differences between total annual precipitation in Uvalde and Hondo in 1991 probably result from intense local thunderstorms. On the basis of annual precipitation, the differences in the estimated duties of water between years and between the counties are reasonable.

Some differences in the duties of water between years and between the counties also could result from differences in farming practices used in the fields selected for measurements. Fields were selected for measurements primarily because the owners were willing to cooperate with the study, resulting in samples that were neither random nor independent. Determining the quantitative effect of precipitation or of individual farming practices was beyond the scope of this project.

The number of acres of each irrigated crop in each county was multiplied by the duty of water for that crop in that county to give the total quantity of water pumped in each county to irrigate crops in 1991 (table 2). All cotton was assumed to be irrigated because no fields of nonirrigated cotton were observed in the calibration sites. The duty of water was applied to the entire calculated or reported area of each irrigated crop although some fields of that crop might have received little or no irrigation in 1991, depending on the quantity and distribution of precipitation and on individual farming practices. The quantities of water pumped from the Edwards aquifer in 1991 to irrigate corn and cotton in Uvalde County were calculated as 28,000 and

Table 2. Areas of irrigated crops and quantity of water pumped from the Edwards aquifer to irrigate crops in Uvalde and Medina Counties, Texas, 1991

[values are rounded to two significant figures]

Crop type	Uvalde County			Medina County			Total pumpage (acre-feet)
	Crop area (acres)	Duty of water (feet)	Pumpage (acre-feet)	Crop area (acres)	Duty of water (feet)	Pumpage (acre-feet)	
			USGS[1]				
Corn	14,000	2.0	28,000	9,700	0.70	6,800	35,000
Cotton	17,000	2.2	37,000	10,000	1.1	11,000	48,000
Total	31,000		65,000	20,000		18,000	83,000
			ASCS[2]				
Corn	11,000	2.0	22,000	14,000	.70	9,800	32,000
Cotton	5,000	2.2	11,000	4,300	1.1	4,700	16,000
Milo	1,800	1.0	1,800	1,500	.46	700	2,500
Small grains	2,800	.92	2,600	420	.75	320	2,900
Other	13,000	1.5	20,000	3,200	1.9	6,100	26,000
Total	34,000		57,000	23,000		22,000	79,000

[1] Crop areas calculated by the U.S. Geological Survey from Landsat Thematic Mapper data.
[2] Crop areas reported by the U.S. Department of Agriculture, Agricultural Stabilization and Conservation Service.

37,000 acre-feet, respectively. The quantities pumped in Medina County were calculated as 6,800 acre-feet for corn and 11,000 acre-feet for cotton. The total quantity of water pumped in 1991 from the Edwards aquifer for the irrigation of crops in Uvalde and Medina Counties, calculated using the USGS estimates of crop areas from Landsat TM data, was about 83,000 acre-feet; the quantity of water pumped calculated from data reported by the ASCS estimates was about 79,000 acre-feet—a difference of about 5 percent.

The total area irrigated in Uvalde and Medina Counties in 1989 was about 71,000 acres, and the total quantity of water pumped from the Edwards aquifer for the irrigation of crops was about 190,000 acre-feet, calculated using Landsat MSS data (Raymond and others, 1992, table 4). This represents a decrease of about 28 percent in the number of acres irrigated and about 56 percent in the quantities of water pumped between 1989 and 1991. Most of this decrease probably resulted from substantially greater precipitation in 1991 than in 1989, particularly in Medina County.

SUMMARY AND CONCLUSIONS

Annual estimates of the quantities and uses of water pumped from the Edwards aquifer in Uvalde and Medina Counties in south-central Texas are provided by the USGS in cooperation with the Edwards Underground Water District. Remote-sensing data from the Landsat MSS sensor for 1989 was evaluated previously to provide areas of irrigated crops necessary to make reliable estimates of pumpage for irrigation. This report describes a technique for the identification of irrigated crops and the estimation of crop acreages using Landsat TM data for 1991.

Only one usable TM image, August 10, was acquired over the study area in 1991, primarily because of cloud cover associated with greater than normal precipitation during the growing season and technical problems with a second cloud-free image. Some irrigated crops, including corn and milo, usually have been harvested before August in the study area. These crops could be identified only by the appearance of the stubble in corn and milo fields on August 10. Bands 2, 3, 4, and 5, spanning a range of 0.52 to 0.90 μm and 1.55 to 1.75 μm, were selected for the analysis because they contained the most spectral information about vegetation and bare soil.

The image was georeferenced so that ARC/INFO could be used to combine the classified image with other geographic data and to prepare illustrations for publication. The maximum-likelihood, unsupervised-classification procedure in ELAS was used to classify the image. Vegetation distribution maps, prepared by field reconnaissance in two parts of the study area, permitted calibration of the classification and identification of the ground-cover types that were classified.

The classification produced 49 ground-cover classes, which subsequently were combined using information from the vegetation distribution maps to form the following 6 ground-cover types: irrigated corn, nonirrigated corn and grasses, cotton, nonirrigated milo and grasses, brush, and bare soil. Some overlap between nonirrigated corn, milo, and grasses was attributed to similarities between stubble and bare soil in harvested fields and with grasses in noncultivated areas. The ground-cover types corn and cotton also contained fields of other crops growing in August, including cane, pasture, alfalfa, and vegetables. The bare soil type included all nonvegetated surfaces not identified in the image as harvested fields of corn or milo.

Substantial areas identified as irrigated crops were known not to be irrigated or irrigated with surface water. The areas most likely to contain crops irrigated with water from the Edwards aquifer were identified on 7-1/2-minute quadrangles augmented by aerial photographs taken in 1989. These probable irrigated areas were digitized from the maps and combined with the classified image to isolate the parts of the study area irrigated with water from the Edwards aquifer. The number of acres of each ground-cover type in each county was calculated as the product of the number of pixels of that type in the probable irrigated areas of the county multiplied by 0.22 acre per pixel.

Areas calculated for irrigated crops were 31,000 acres for Uvalde County, about 35 percent less than the area calculated using Landsat MSS data in 1989, and 20,000 for Medina County, about 13 percent less than in 1989. The total area irrigated in 1991 was about 28 percent less than the area irrigated in 1989. Differences were attributed to differences in precipitation resulting in fewer fields being irrigated in 1991 than in 1989, refinements in the boundaries of the probable irrigated areas in 1991 compared to 1989, and differences in the classification results using Landsat TM and MSS data. The total number of acres of irrigated crops estimated using Landsat TM data was about 9 percent lower in Uvalde County and about 13 percent lower in Medina County than the number of acres reported by the ASCS. Probable causes of the discrepancies include the following: (1) errors in adjusting the ASCS numbers to include all fields in the study area irrigated with water from the Edwards aquifer; (2) inclusion of some irrigated corn and milo in the nonirrigated ground-cover types; and (3) errors in identifying the number and size of probable irrigated areas.

Quantities of water pumped from the Edwards aquifer to irrigate crops in 1991 were estimated as 65,000 acre-feet for Uvalde County and 18,000 acre-feet for Medina County. The total quantity of water pumped from the Edwards aquifer to irrigate crops in these counties was about 56 percent less in 1991 than in 1989. Differences between 1989 and 1991 pumpages were attributed primarily to greater precipitation in 1991 than in 1989, particularly in Medina County, resulting in lower duties of water and less supplemental irrigation. The total quantity of water pumped in 1991 was calculated from TM data as about 83,000 acre-feet, compared to about 79,000 acre-feet calculated from data reported by the ASCS—a difference of about 5 percent.

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