Evaluation of the use of Remote-Sensing Data to Identify Crop Types and Estimate Irrigated Acreage, Uvalde and Medina Counties, Texas, 1989

By Lee H. Raymond, Gregory M. Nalley, and Paul L. Rettman

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CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS

Multiply	By	To obtain
acre	0.4047	hectare
acre-foot	0.001233	cubic hectometer
foot	0.3048	meter
mile	1.609	kilometer

EVALUATION OF THE USE OF REMOTE-SENSING DATA TO IDENTIFY CROP TYPES AND ESTIMATE IRRIGATED ACREAGE, UVALDE AND MEDINA COUNTIES, TEXAS, 1989

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ABSTRACT

Remote-sensing data were used to estimate that 190,000 acre-feet of water was pumped from the Edwards aquifer in 1989 to irrigate crops in Uvalde and Medina Counties. Landsat digital satellite images for March and July 1989 were combined and classified to identify the areas of crops irrigated with water from the Edwards aquifer in the two counties. Normalized difference, the difference between the infrared and red reflectance values divided by the total of those values, was used to discriminate vegetative from nonvegetative ground cover. The images subsequently were classified using maximum likelihood, an unsupervised classification procedure. Detailed vegetation distribution maps of two calibration sites in the study area, and boundaries of the areas probably irrigated in 1989, helped to interpret the results and to separate probable irrigated areas from the rest of the image.

Results were verified using 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 remote-sensing data were about 8 percent higher for Uvalde County and about 4 percent higher for Medina County than the areas reported by the ASCS. Irrigated-crop areas subsequently were multiplied by the respective duties of water to calculate the total quantity of water pumped from the aquifer for irrigation. Pumpage did not differ for the two estimates of crop areas for Uvalde County and differed by about 3 percent for Medina County.

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 21 percent of the total quantity pumped from the aquifer for all purposes in 1988 (Nalley, 1989, table 4)--has been estimated from crop-acreage data provided by Federal, State, and local agencies, and 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

Previous studies in Arizona and California (Raymond and Owen-Joyce, 1987; Raymond and Rezin, 1989) have developed a technique that uses remote sensing to identify and calculate areas of vegetation, in conjunction with field studies to determine the average quantity of water used by each type of vegetation. In these studies, three Landsat digital satellite images (late winter, late spring, and midsummer) were combined and classified. Major crops in the study areas were identified with as much as 90-percent accuracy (Raymond and Rezin, 1989, table 2). Water-use rates for crops were calculated from the results of field studies conducted by Erie and others (1965) and adjusted for climatic conditions in the study areas. The total annual evapotranspiration calculated by multiplying crop acreages by their corresponding water-use rates agreed with the total annual consumptive use by vegetation, calculated using a water budget of measured and estimated inflows and outflows, within about 10 percent in each of 4 years (Raymond and Owen-Joyce, 1987, p. 22).

The technique used in the Arizona and California studies was successful partly because conditions for collecting remote-sensing data of irrigated crops were particularly favorable in hot, dry climates. Cloud cover, which obscures the ground cover in remote-sensing images, is less frequent than in other types of climates. The warm climate results in a 12-month growing season and nonirrigated vegetation is minimal, except in the flood plains of major watercourses where phreatophytes have access to ground water. Water used by cultivated plants is supplied entirely by irrigation, except during years when precipitation greatly exceeds normal quantities. In cooler or more humid parts of the country, problems with collecting data during the growing season are more likely.

In 1989, the USGS, in cooperation with the Edwards Underground Water District, established a project to evaluate the use of the technique developed in Arizona and California, modified as necessary for local conditions, and its application to south-central Texas. The study area selected for the project is west of San Antonio (fig. 1) and includes all of the agricultural land in Uvalde and Medina Counties. Principal irrigated crops in the study area in 1989 were corn, cotton, and small grains (wheat and oats) with a few fields each of alfalfa, cane, and vegetables. Nonirrigated crops included milo, some corn, some fields of small grains, and pasture; however, supplemental

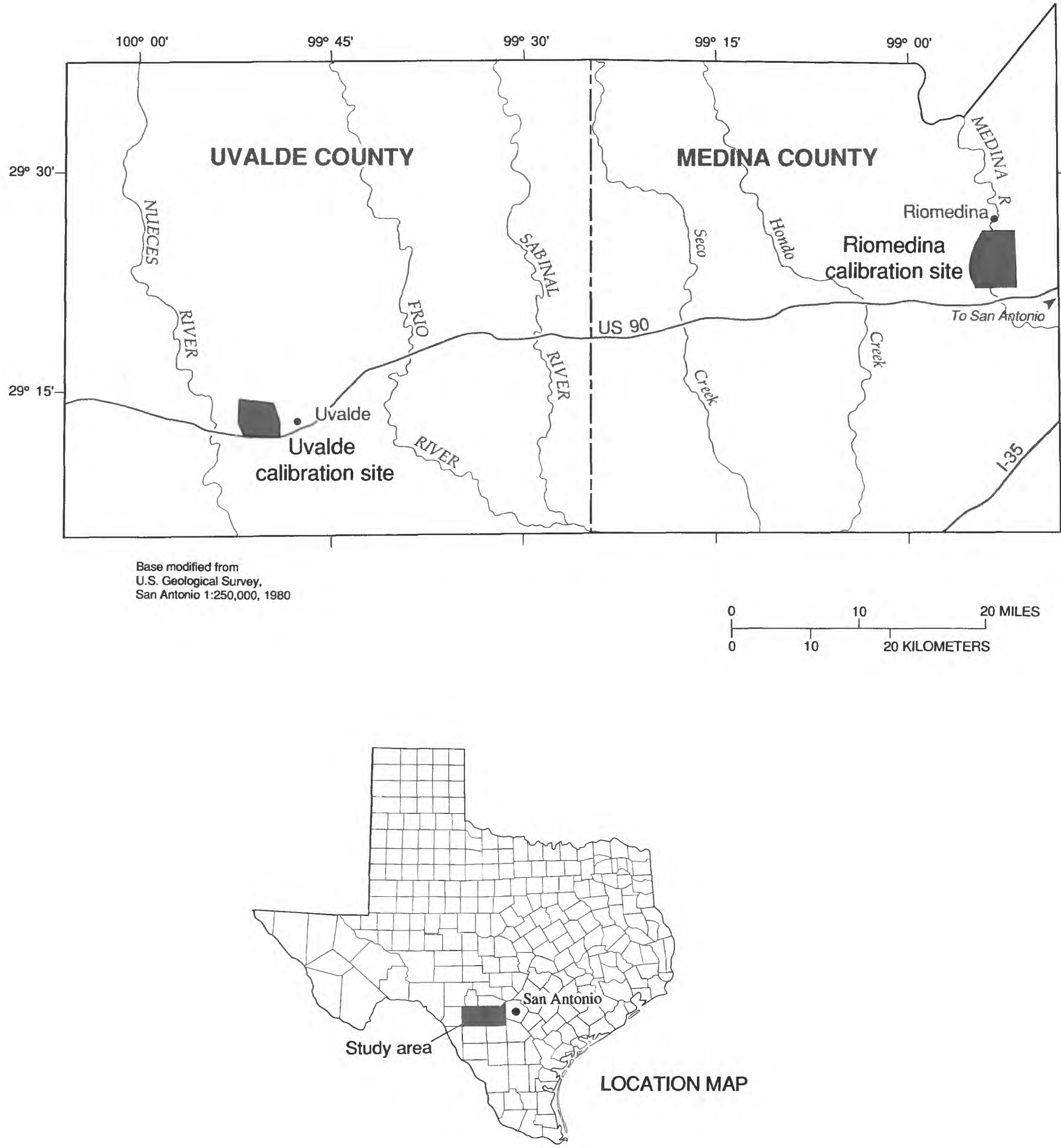


Figure 1.--Location of study area and calibration sites.

irrigation was applied to a few fields of each of these crops in some parts of the study area. Noncultivated vegetation included mesquite, oak, pecan, other tree species, and various kinds of shrubs (collectively referred to as brush in this report); and grasses and other herbaceous vegetation (collectively referred to as grasses).

Purpose and Scope

This report describes the technique that was developed to identify and estimate areas of irrigated crops using remote-sensing data from the Landsat satellite. Data for 1989 were used to estimate the quantity of water pumped from the Edwards aquifer for irrigation in Uvalde and Medina Counties, Texas.

Acknowledgments

The U.S. Department of Agriculture, Soil Conservation Service, National Mapping Center provided computer facilities for digital-image processing. The U.S. Department of Agriculture, Agricultural Stabilization and Conservation Service (ASCS) provided their records of irrigated-crop areas in Uvalde and Medina Counties.

CROP IDENTIFICATION BY CLASSIFICATION OF REMOTE-SENSING 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 since 1972.

Numerous techniques using Landsat 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 technique used in this study in south-central Texas and of the methods used for crop identification and calibration of the classified images. A more detailed description of the basic classification technique may be found in Raymond and Rezin (1989).

The computer software package used for the following analysis was ELAS (Earth Resources Laboratory Applications Software). References to specific parts of the software manual (Graham and others, 1985) are included here for the convenience of the reader who wants a more detailed technical description of the technique than this report provides.

Description of the Classification Technique

A preliminary classification indicated that spectral differences between irrigated vegetation types were not sufficient at Landsat MSS (multispectral scanner) resolution to separate them from each other or from some types of nonirrigated vegetation in a single image. Therefore, a composite of digital images that included spectral and temporal differences between vegetation types was generated for the classification. The technique selected for classification was multispectral, multitemporal classification of Landsat MSS images.

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 may not be available during the parts of the growing season most favorable for mapping a particular vegetation type in any given year.

Images for the 1989 classification were acquired for March 29 and July 11. Corn and cotton had the largest irrigated areas of all crops in the study area in 1989. Visual inspection of false-color composites generated from each of the digital images showed that corn was identifiable on both images; cotton was identifiable only on the July image. Some differences in the nonirrigated vegetation also were apparent between the two images. A third image, acquired between the corn and cotton harvests, or in the early spring when only nonirrigated vegetation was apparent, probably would have provided additional data to help distinguish vegetation types (based on the results discussed in Raymond and Rezin, 1989). However, additional cloud-free images of the study area during the 1989 growing season were not available. (A cloud-free image was defined as one with 10-percent or less cloud cover over the study area.)

The Landsat MSS scans the ground as the satellite passes over it and records electromagnetic reflectance in four bands of the spectrum: green (band 1), 0.4-0.5 μm (micrometers); red (band 2), 0.6-0.7 μm; and near-infrared (bands 3 and 4), 0.7-0.8 and 0.8-1.1 μm, respectively. Each scan line is composed of pixels (picture elements), with each pixel containing the average reflectance of approximately 1 acre. The electromagnetic reflectance of each pixel received by the 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 four spectral bands, ranging from 0 (black, or no reflectance) to 127 (white, or total reflectance).

Georeferencing is the process of establishing the geographic location of each pixel in an image and coding the map coordinates as attributes of the pixel. Georeferencing is required when images are to be combined with each other prior to classification or combined with other spatial-data layers. Ground-control points, such as road intersections and buildings, 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 U.S. Geological Survey 7-1/2-minute quadrangles. A georeferencing program (Graham and others, 1985, p. PMGE 1) was used to match the row and column numbers of the ground-control pixels to their UTM coordinates from the maps. The program mapped the images by generating UTM coordinates for each pixel in the image. The resulting linear grid consisted of pixels of a uniform size, resampled to a precision of 0.62 acre each.

Healthy vegetation absorbs red radiation (0.6-0.7 μm) and reflects near-infrared radiation, particularly in the 0.8-1.1 μm range. Water, soil, rocks, and other nonvegetative ground cover typically reflects about the same quantity of (or more) radiation in the red band than in the near-infrared band of the spectrum. This characteristic spectral response of vegetation compared with that of nonvegetation is used to distinguish the vegetation from other types of ground cover in an image. Normalized difference was used to digitally enhance the vegetation response in each image for this study. Normalized difference is the difference between the digital numbers of each pixel in the red and near-infrared bands divided by the total reflectance in both bands. The relation may be expressed mathematically as follows (modified from Myers, 1983, p. 2,151):

$$ND = (IR - R) / (IR + R) \qquad (1)$$

where ND is normalized difference for each pixel in an image;
IR is digital number of each pixel in the near-infrared band (band 4); and
R is digital number of the corresponding pixel in the red band (band 2).

Normalized differences calculated for the March 29 and July 11 images were combined into a single 2-layer image file. The file then was classified using the unsupervised maximum likelihood classification algorithm (Graham and others, 1985, p. A13-A17). The output from the classification included a sequential identification number of each ground-cover class and the average normalized difference of each class on each image date.

Calibration of the Classification

The purpose of classification is to group pixels into classes based on similar reflectance characteristics at the time each image is acquired. The assumption made 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 may 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, may have the same spectral and temporal characteristics on the particular image dates selected and may be grouped into the same ground-cover class. Also, spectral and temporal 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. Therefore, classifications require calibration and interpretation in one or more locations where the ground-cover types are 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. In 1989, two calibration sites were required in the study area to meet all of the criteria.

Crops were identified in each of the calibration sites by field reconnaissance and recorded on 7-1/2-minute quadrangles. Field reconnaissance was conducted for the 1989 classification on June 9. On that date, nearly all of the major crops (irrigated and nonirrigated) that grew in the study area could be identified on the ground. Double cropping is uncommon in this region, and winter crops, such as small grains, could be identified by the stubble that remained in many of the fields. Corn and milo had begun to head. Color differences between the two types of heads made them easy to distinguish, even from a distance. Cotton was almost fully grown and had begun to bloom.

Uvalde Calibration Site

The Uvalde calibration site was near the western edge of the study area (fig. 1) in Uvalde County. A detailed vegetation distribution map was prepared (fig. 2) and included about 7,000 acres of vegetation. The fields were large, with a relatively large proportion of corn and cotton. Unbroken areas of these crops exceeded 300 acres in some places. Fallow fields, some with grain stubble and pasture, also covered fairly large areas. A few fields of small grains, vegetables, and milo or grasses were identified. The remainder of the vegetated area was covered with brush.

Most of the fields in the Uvalde calibration site were irrigated. Cotton distribution appeared to be quite uniform. Corn distribution was more variable, with sparsely covered or bare spots and areas of dead plants apparent in some of the fields. Some of the pasture fields were irrigated and green with grasses, and some contained only sparse or dormant vegetation. In some fields, stubble already had been plowed under and was difficult to identify as small grains from the previous winter or as corn or milo from the previous summer. Some fields in the calibration site were not mapped because they were inaccessible. In the adjacent town of Uvalde, lawns, gardens, cemeteries, and other areas of vegetation were noted but not mapped.

Riomedina Calibration Site

The Riomedina calibration site was in the northeastern part of the study area (fig. 1) in Medina County. A detailed vegetation distribution map was prepared (fig. 3) and included an area of about 3,500 to 4,000 acres of vegetation. Corn was the most common irrigated-crop type. Fields of milo or grasses (irrigated and nonirrigated) were common. A larger proportion of the fields in the Riomedina calibration site appeared to be nonirrigated than fields in the Uvalde calibration site, perhaps because many plants were able to utilize shallow ground water in and adjacent to the Medina River flood plain. Plants (particularly corn and milo) in nonirrigated fields were smaller and more variable in distribution than those in the irrigated fields.

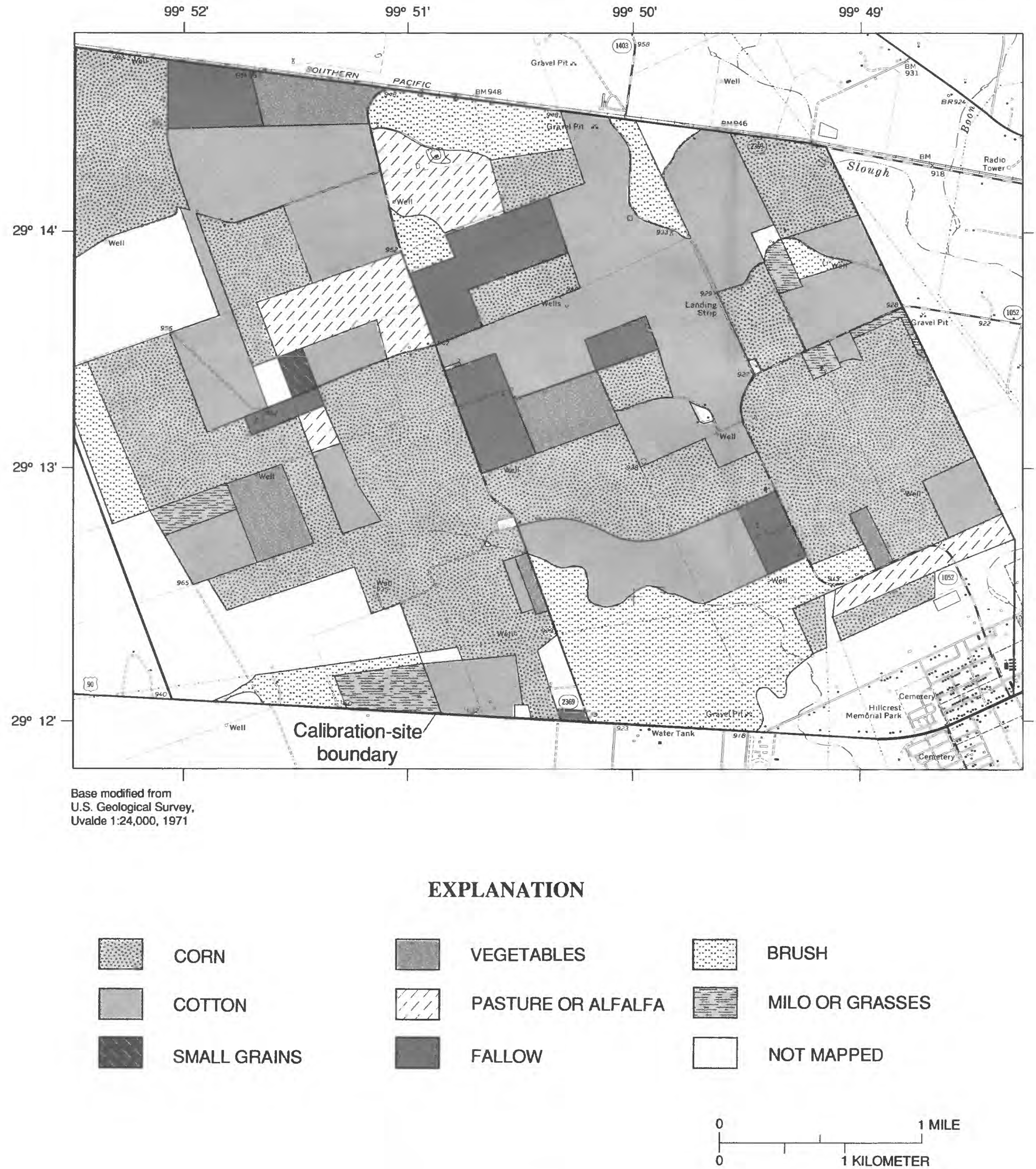


Figure 2.--Uvalde calibration site and vegetation distribution.

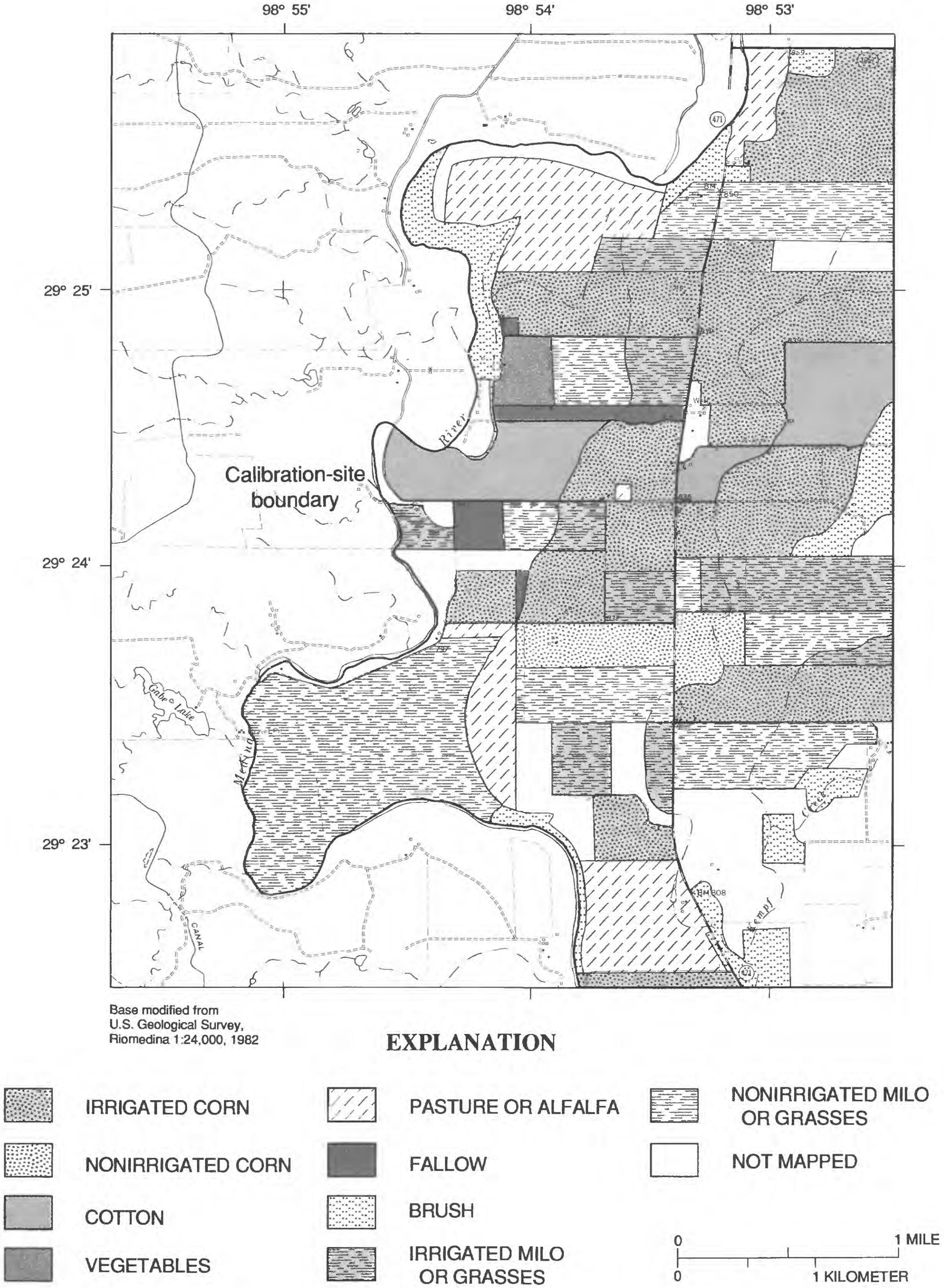


Figure 3.--Riomedina calibration site and vegetation distribution.

These plants respond to soil moisture distribution, resulting from variations in soil texture, during the dry parts of the growing season. A small number of fields of pasture or alfalfa, isolated fallow fields (one containing stubble), vegetable fields, and small-grain fields were identified. Brush was common along the Medina River and its tributaries.

Interpretation of the Classification

Interpretation of the classification was made using the classification results and the two vegetation maps (figs. 2 and 3). Most of the ground-cover classes (table 1) represented vegetation ground-cover types because normalized difference enhances vegetation reflectance characteristics. The reflectance characteristics of nonvegetated types of ground cover were minimized, causing them to be compressed into only a few ground-cover classes. The dates for which large or small normalized difference values were calculated in ground-cover classes indicated the growing seasons of the particular vegetation types.

Vegetation maps prepared for the calibration sites were required to identify specific vegetation types in the image classification. Ground-cover classes were identified throughout the study area as the vegetation type they represented in the vegetation maps. 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 on each image and were combined into the same class, the vegetation type covering the largest area in the vegetation maps was selected because it had the greatest probability of being correct. Thus, some minor vegetation types were not correctly identified using this approach.

The largest ground-cover class in the calibration sites was corn (class 15). Considerable overlap in normalized difference between corn, many grasses, and field borders resulted in a combined classification of these vegetation types. Cotton was represented by ground-cover classes 4, 5, 12, 26, and 33. Together, they comprised the most clearly defined and uniform fields of a vegetation type in this study, although considerable overlap with noncultivated vegetation was evident outside the calibration sites. Classes 3, 6, 8, 9, 10, 11, 13, 14, and 21 represented small grains; class 25 represented pasture. These two vegetation types frequently were misclassified with each other, and occasionally with fallow fields. The misclassification was caused by the large range in the percentage of ground covered by vegetation within the pasture and fallow fields, and the large range of senescence of the small-grain fields. The small grains could not be distinguished from some of the other cultivated and noncultivated grasses in the March image. Grasses included classes 1, 16, 17, 22, and 28. Classes 2, 18, 19, 23, 24, 29, and 30 were composed predominantly of brush. The areas covered by classes 27 and 31 were not included in the calibration sites; therefore, the vegetation types were classified as unknown. Field reconnaissance outside the calibration sites indicated that alfalfa and cane were part of these classes, but their observed areas were small.

Table 1. Average normalized difference and designation of the ground-cover classes

[Average normalized difference, the difference between infrared and red reflectance values divided by the sum of the values]

Ground-cover class number	Average normalized difference March 29	Average normalized difference July 11	Ground-cover class
1	59	52	Grasses.
2	48	0	Brush and grasses. Coded as brush.
3	117	0	Small grains.
4	62	141	Cotton.
5	67	84	Cotton and field borders.
6	138	0	Small grains.
7	0	0	Fallow.
8	99	0	Small grains.
9	148	0	Small grains.
10	90	0	Small grains.
11	76	0	Small grains.
12	8	140	Cotton.
13	107	0	Small grains.
14	82	0	Small grains.
15	50	34	Corn, grasses, and field borders. Coded as corn.
16	56	61	Grasses.
17	64	35	Grasses.
18	64	0	Brush.
19	53	0	Brush.
20	12	0	Fallow.
21	128	0	Small grains.
22	99	105	Grasses.
23	54	6	Brush.
24	69	0	Brush.
25	84	100	Pasture.
26	0	139	Cotton.
27	111	126	Unknown. Not in calibration sites.
28	40	45	Grasses.
29	58	0	Brush.
30	44	0	Brush.
31	147	64	Unknown. Not in calibration sites.
32	27	0	Fallow.
33	44	128	Cotton.

Fields in the Riomedina calibration site and adjacent areas consisted primarily of nonirrigated vegetation, which is typified by an uneven distribution of ground cover. Some corn, cotton, small grains, and fallow fields had relatively uniform ground cover, but many of the pixels in each class were scattered and mixed. Most of the area consisted of the Medina River flood plain and noncultivated hills and ridgetops. The vegetation map indicated that some of the ground-cover classes identified as grass probably included milo, but most appeared to be noncultivated vegetation east of the flood plain, or adjacent to the Medina River. Numerous pixels from ground-cover classes identified as irrigated crops, particularly corn, milo, and some cotton, appeared in noncultivated areas. The spectral and temporal characteristics of these noncultivated areas were similar to those of the crops in the classification.

Based on these results, identification of vegetation types could be considered fairly reliable within cultivated areas, as determined by the vegetation maps. Outside the cultivated areas, however, the ground-cover classes were dominated by mixed vegetation types. These mixtures of pixels in the ground-cover classes precluded the direct calculation of irrigated crop areas by using total pixel counts for each class. Subdivision of the digital images, discussed in the next section, was required to further define the areas of irrigated, nonirrigated, and noncultivated vegetation in the study area.

ESTIMATION OF IRRIGATED ACREAGE

The areas most probably containing 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 combining them with the classified image to calculate areas of irrigated crops is similar to the technique used by most geographic information systems.

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 indicate many field boundaries, but only those that existed when each of the maps was made. Many of those fields in the proximity of mapped water wells probably were irrigated. Fields may 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 by comparing the maps with records of well inventories (U.S. Geological Survey, unpublished data) conducted in the study area since the topographic maps were made; with unpublished data from the U.S. Department of Agriculture, Soil Conservation Service; and with field observation. These areas (hereafter referred to as probable irrigated areas) may contain not only the irrigated fields, but also nonirrigated and noncultivated vegetation.

Boundaries of probable irrigated areas were drawn on the maps, and the polygons thus formed were coded by county, map number, and sequence number. Separate polygons were drawn for parts of probable irrigated areas located on two or more adjacent maps. An example of the coded polygons created from boundaries of probable irrigated areas for the Uvalde 7-1/2-minute quadrangle is shown in figure 4. Each map was geographically registered by entering the UTM coordinates of the corner ticks. Vertices of polygons digitized from the maps were assigned the corresponding UTM coordinates by ELAS and filed by code name (Graham and others, 1985, p. DGTZ 1-2).

Digitized polygons of the probable irrigated areas were registered to the classified image by matching the corresponding UTM coordinates. The polygon boundaries formed a mask that separated the probable irrigated areas within them from the rest of the image. The probable irrigated areas were named for the polygons that had enclosed them and then were stored as individual image files (Graham and others, 1985, p. PLYX 1).

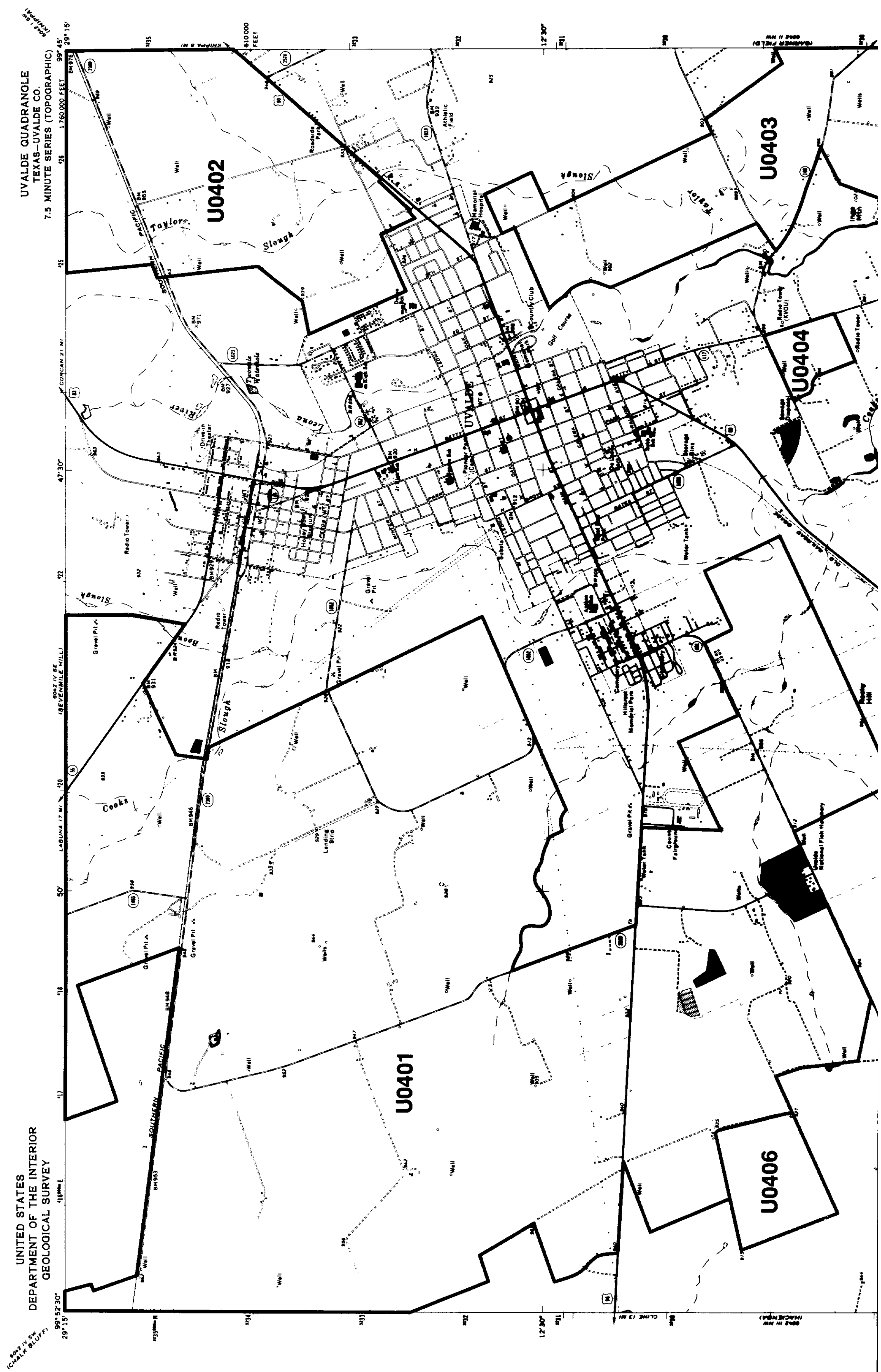
Determination of Acreages

The number of acres covered by each class in each of 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 0.62 acre per georeferenced pixel. The program output for each probable irrigated area included the class numbers, number of pixels in each class, statistical parameters for the class, percent of the probable irrigated area covered by that class, and the number of acres covered by the class (Graham and others, 1985, p. PLYA 1-4). The number of acres of each ground-cover type in Uvalde and Medina Counties equals the sum of the areas of each class identified as that type, grouped by county (table 2).

Table 2. Areas of principal ground-cover types for Uvalde and Medina Counties

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

Ground-cover type	Uvalde County	Medina County	Total area
Corn	16,000	9,000	25,000
Cotton	19,000	12,000	31,000
Small grains	12,000	1,500	14,000
Unknown	480	220	700
Pasture	330	340	670
Fallow	15,000	3,700	19,000
Brush	16,000	1,800	18,000
Grasses	6,700	6,700	13,000
Total area	86,000	35,000	120,000


UVALDE QUADRANGLE
TEXAS–UVALDE CO.
7.5 MINUTE SERIES (TOPOGRAPHIC)
UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
U0401
U0402
U0403
U0404
U0406
UVALDE

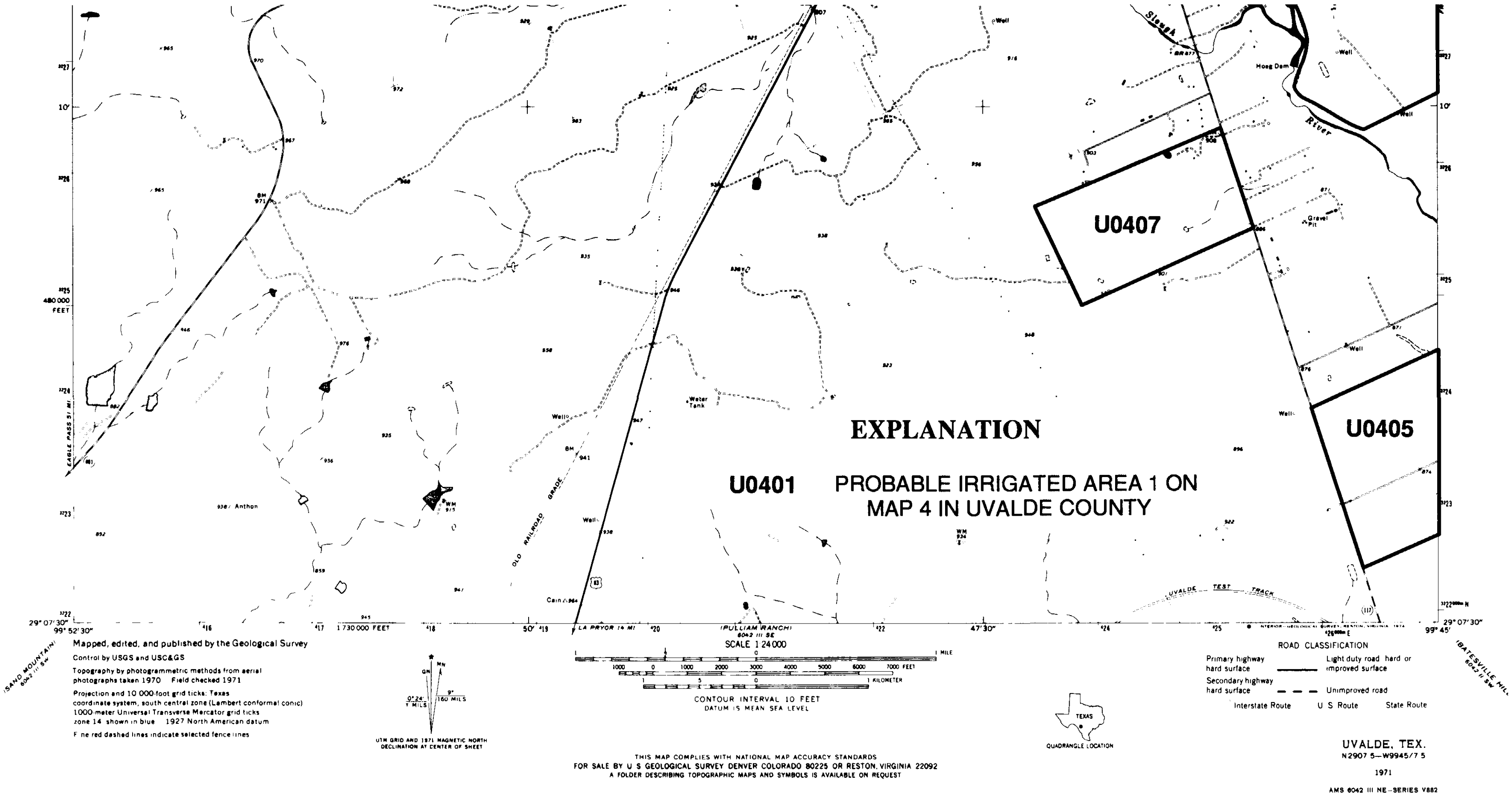


Figure 4.--Uvalde 7-1/2-minute quadrangle with boundaries of probable irrigated areas, 1989.

Comparison of Reported and Estimated Acreages

Data on areas of irrigated crops in Uvalde and Medina Counties for 1989 were obtained from ASCS records. Parts of the areas, known to be irrigated with surface water, were subtracted from the totals. The areas of crops irrigated with water from the Edwards aquifer, estimated as described here, are listed in table 3 along with the areas of irrigated crops reported by ASCS.

Table 3. Areas of irrigated crops for Uvalde and Medina Counties, 1989

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

	USGS[1]			ASCS[2]	
Crop type	Uvalde County	Medina County	Crop type	Uvalde County	Medina County
Corn	16,000	9,000	Corn	21,000	16,000
Cotton	19,000	12,000	Cotton	13,000	4,500
Small grains	12,000	1,500	Small grains	9,000	1,100
			Milo	1,200	500
Unknown	480	220			
Pasture	330	340			
Total	48,000	23,000	Total	44,000	22,000

[1] Crop areas calculated by the U.S. Geological Survey (present study).
[2] Crop areas reported by the U.S. Department of Agriculture, Agricultural Stabilization and Conservation Service; modified to include only areas irrigated with water from the Edwards aquifer.

The total number of acres of irrigated crops estimated by the USGS using remote-sensing data was about 8 percent higher in Uvalde County and about 4 percent higher in Medina County than the number of acres reported by the ASCS. Probable causes of the discrepancies include: misidentification of minor summer crops, such as cotton; inclusion of some corn and milo in the ground-cover type "grasses"; and errors in identifying the number and size of probable irrigated areas.

Some differences also may be attributed to differences in the ways in which the areas of crops are determined. Landsat data include reflectance values of the ground cover of the crop within the vegetated area; 38 acres planted to corn might include 35 acres of healthy corn and 3 acres of sparse or dead corn. In this case, Landsat would record 35 acres of pixels with the reflectance characteristics of corn and 3 acres with the reflectance characteristics of fallow fields or grasses. The ASCS calculates crop areas based on field size, excluding roads, buildings, and other nonvegetated surfaces. A 40-acre field with 38 acres planted to corn was reported as 38 acres of corn.

As previously mentioned, some overlap was evident between the classes identified as small grains, pasture, and fallow fields. However, the three vegetation types were mostly nonirrigated, with the exception of supplemental irrigation in some grain and pasture fields. Inclusion of some areas of non-irrigated or noncultivated vegetation within the boundaries that isolated probable irrigated areas from the rest of the study area may have contributed to the overall error in calculating areas of irrigated crops.

CALCULATION OF THE QUANTITY OF IRRIGATED WATER PUMPED FROM THE EDWARDS AQUIFER, 1989

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 average quantity of water applied to a given crop type over an area and time for which the data apply was defined in this study as the duty of water. The duties of water for Uvalde and Medina Counties in 1989 were calculated using individual fields of representative crops, and subsequently averaged by county. 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. 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 for each irrigated-crop type in Uvalde and Medina Counties in 1989, is listed in table 4.

The number of acres of each 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 1989 (table 4). The duty of water for small grains was applied to the entire calculated or reported area of small grains although as much as two-thirds of the crop might receive little or no irrigation, depending on the quantity and distribution of winter precipitation. (Determining the quantity and distribution of precipitation was beyond the scope of this project.) The quantity of water pumped did not differ for the USGS and ASCS estimates of crop areas in Uvalde County and differed by about 3 percent in Medina County, within the limit of 2 significant figures as determined by the number of acres per pixel. The total quantity of water pumped in 1989 from the Edwards aquifer for the irrigation of crops in Uvalde and Medina Counties was about 190,000 acre-feet.

Although areas of individual crops varied between the USGS and ASCS figures, variations in the duty of water offset these differences, resulting in comparable pumpage calculated from the two estimates of acreages. The

Table 4. Quantity of water pumped from the Edwards aquifer to irrigate crops in Uvalde and Medina Counties, 1989

[ft, feet; acre-ft, acre feet; --, no data; values are rounded to two significant figures]

Crop type	Uvalde County: Number of acres	Uvalde County: Duty of water (ft)	Uvalde County: Pumpage (acre-ft)	Medina County: Number of acres	Medina County: Duty of water (ft)	Medina County: Pumpage (acre-ft)	Total Pumpage (acre-ft)
USGS [1]							
Corn	16,000	3.8	61,000	9,000	3.2	29,000	90,000
Cotton	19,000	2.6	49,000	12,000	2.6	31,000	80,000
Small grains	12,000	1.4	17,000	1,500	1.0	1,500	18,000
Unknown	480	--	--	220	--	--	--
Pasture	330	3.3	1,100	340	2.9	990	2,100
Milo	--	--	--	--	--	--	--
Total	48,000		130,000	23,000		62,000	190,000
ASCS [2]							
Corn	21,000	3.8	80,000	16,000	3.2	51,000	130,000
Cotton	13,000	2.6	34,000	4,500	2.6	12,000	46,000
Small grains	9,000	1.4	13,000	1,100	1.0	1,100	14,000
Pasture	--	--	--	--	--	--	--
Milo	1,200	0.67	800	500	0.67	340	1,100
Total	44,000		130,000	22,000		64,000	190,000

[1] Crop areas calculated by the U.S. Geological Survey (present study).

[2] Crop areas reported by the U.S. Department of Agriculture, Agricultural Stabilization and Conservation Service; modified to include only areas irrigated with water from the Edwards aquifer.

number of acres of corn was greater in the ASCS estimates than in the USGS estimates; areas of cotton and small grains were greater in the USGS estimates. Corn had the largest calculated duty of water, small grains had the smallest, and the duty of water for cotton was between those of the other two crops. A larger pumpage was calculated for corn and a smaller pumpage was calculated for the other two crops using the ASCS estimates than using the USGS estimates. Therefore, the differences were offset when crops were combined by county.

Correct calculation of the quantity of water pumped for irrigation depended primarily on the accuracies of the duties of water and of the total crop area. The calculation was less sensitive to the crop distribution within the probable irrigated areas as long as the total irrigated areas were similar between the two estimates of crop acreages. These sources of error in the calculations are consistent with the sources of error reported in Raymond and Owen-Joyce (1987) and Raymond and Rezin (1989).

SUMMARY AND CONCLUSIONS

A classification technique that uses remote-sensing data from Landsat digital satellite images was evaluated to calculate the areas of crops irrigated with water from the Edwards aquifer in Uvalde and Medina Counties, Texas. The technique, developed previously for studies in Arizona and California, was modified for differences in vegetation and growing conditions at the Texas site and applied to satellite images from March and July 1989.

The purpose of the image classification was to group image pixels into classes, based on similar reflectance characteristics at the time each image was acquired, with the assumption that pixels with the same spectral and temporal characteristics represented the same types of ground cover. Normalized difference, the difference between the infrared and red reflectance values divided by the total of those values, was used to discriminate vegetative from nonvegetative ground cover. The images subsequently were classified using maximum likelihood, an unsupervised classification procedure. Detailed vegetation maps of two calibration sites in the study area, and boundaries of the areas probably irrigated in 1989, helped to interpret the results and to separate the classification into smaller images containing only those areas where irrigation was probable. The final calibrated classified images yielded areas of irrigated, nonirrigated, and noncultivated ground-cover types in the probable irrigated areas of Uvalde and Medina Counties.

Ground-cover classes typically overlapped where spectral and temporal differences between ground-cover types were not distinctive on the two image dates at 0.62-acre resolution. On the basis of previous studies in Arizona and California, a third image collected in late winter or later in the summer may have provided additional data that would help to further separate ground-cover classes. However, no additional cloud-free images were available for the 1989 growing season.

Corn, cotton, and small grains (wheat and oats) were the principal irrigated crops in 1989. Milo, some corn, and some small grains were the principal nonirrigated crops. Brush and grasses were the principal noncultivated ground-cover types. Most of the irrigated crops were grown in

Uvalde County. The total number of acres of irrigated crops estimated by this study using remote-sensing data was about 8 percent higher than the number of acres reported by the ASCS for Uvalde County and about 4 percent higher for Medina County.

A duty of water was calculated for each crop in each county using well yields, well operating times, and areas of representative crop fields. The number of acres of each crop was multiplied by the respective duty of water. Results, summed by county for the USGS and ASCS estimates of crop areas, did not differ for Uvalde County and differed by about 3 percent for Medina County. Discrepancies in areas and pumpage estimates for individual crops tended to cancel each other, so that overall totals of water pumped were in agreement. About 190,000 acre-feet of water was pumped in 1989 from the Edwards aquifer for the irrigation of crops in Uvalde and Medina Counties.

Positive conclusions, based on the results of the 1989 classification, include the following: (1) total quantity of water pumped, calculated to 2 significant figures using USGS estimates of crop area, agreed closely with pumpage calculated using ASCS crop-area data; (2) the technique using remote-sensing data to identify and calculate the areas of irrigated crops is rapid, standardized, and reproducible so that subjective interpretation is minimal; (3) computer files containing the crop areas are in a format suitable for rapid computation of pumpage; and (4) crop acreages for all parts of the study area are uniformly easy to obtain.

Several factors produced negative conclusions: (1) irrigated and nonirrigated fields of the same crop are difficult to separate at Landsat MSS resolution; (2) noncultivated vegetation frequently exhibits similar spectral and temporal characteristics to those of the irrigated crops; and (3) even though the study area is considered part of a warm, sunny climate, partial cloud cover is frequent--particularly in the morning, which includes the time of the Landsat overpasses--thus limiting the number of usable images acquired during a given year. The two satellite images collected for the 1989 classification did not contain sufficient information to make a clear distinction between some ground-cover types. On the basis of results of similar studies in Arizona and California, a third image, collected during a different part of the growing season, might substantially reduce this problem.

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