Evapotranspiration Estimates Using Remote-Sensing Data, Parker and Palo Verde Valleys, Arizona and California

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Evapotranspiration Estimates Using Remote-Sensing Data, Parker and Palo Verde Valleys, Arizona and California

By LEE H. RAYMOND and KELLY V. REZIN

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CONTENTS

Abstract **1**
Introduction **1**
    Purpose and scope **1**
    Acknowledgments **3**
Parker Valley **3**
    Crop-classification methods **3**
        Medium-altitude aerial photography **3**
        Satellite images **5**
            Digital-image classification **9**
            Visual photointerpretation of Landsat satellite images **11**
    Evapotranspiration by crops **11**
    Phreatophytes **12**
    Water budget **13**
Palo Verde Valley **13**
    Crop classification **14**
    Evapotranspiration by crops **14**
    Water budget **14**
Discussion **17**
    Comparison of methods **17**
    Evaluation of evapotranspiration estimates **18**
References cited **18**

FIGURES

1. Map showing area of report **2**
2. Map showing Parker Valley test site **4**
3. Medium-altitude color-infrared aerial photographs showing part of the Parker Valley test site **6**
4. Photographs showing Landsat MSS bands and band ratio for the Parker Valley test site, July 18, 1981 **8**
5. Photographs showing video displays of crop classification from Landsat digital satellite data for part of the Parker Valley test site **10**
6. Map showing Palo Verde Valley test site **16**

TABLES

1. Summary of crop classifications from medium-altitude color-infrared aerial photography in the Parker Valley test site, 1982 **7**
2. Summary of crop classifications from Landsat digital satellite images in the Parker Valley test site, 1981 **12**
3. Summary of crop classifications from visual photointerpretation of Landsat satellite images in the Parker Valley test site **13**
4. Water-use rates, in acre-feet, for crops in southern Arizona **14**
5. Evapotranspiration by crops in the Parker Valley test site **15**
6. Evapotranspiration by phreatophytes in the Parker Valley test site **15**
7. Summary of crop classifications from Landsat digital satellite images in the Palo Verde Valley test site, 1981 **17**

Metric Conversion Factors

For readers who prefer to use metric (International System) units rather than inch-pound units, the conversion factors for the terms used in this report are listed below:

Multiply inch-pound unit	By	To obtain metric unit
foot (ft)	0.3048	meter (m)
acre	0.4047	hectare (ha)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)

Evapotranspiration Estimates Using Remote-Sensing Data, Parker and Palo Verde Valleys, Arizona and California

By Lee H. Raymond *and* Kelly V. Rezin

Abstract

In 1981 the U.S. Geological Survey established an experimental project to assess the possible and practical use of remote-sensing data to estimate evapotranspiration as an approximation of consumptive use of water in the lower Colorado River flood plain. The project area was in Parker Valley, Arizona. The approach selected was to measure the areas covered by each type of vegetation, using remote-sensing data in various types of analyses, and to multiply each area by a predetermined water-use rate.

Two calibration and six remote-sensing methods of classifying crop types were compared for cost, accuracy, consistency, and labor requirements. Included were one method each for field reconnaissance using 1982 data, low-altitude (less than 5,000 feet) aerial photography using 1982 data, and visual photointerpretation of Landsat satellite images using 1981 and 1982 data; two methods for medium-altitude (15,000–18,000 feet) aerial photography using 1982 data; and three methods for digital Landsat satellite images using 1981 data. A test of the most promising digital-processing method, which used three image dates, was made in part of Palo Verde Valley, California, where 1981 crop data were more complete than in Parker Valley.

Of the eight methods studied, the two-date digital-processing method was the most consistent and least labor intensive for identifying two or three major crops; visual photointerpretation of Landsat images was the least expensive. Evapotranspiration estimates from crop classifications by all methods differed by a maximum of 6 percent. Total evapotranspiration calculated from crop data and phreatophyte maps in 1981 ranged from 11 percent lower in Palo Verde Valley to 17 percent lower in Parker Valley than consumptive use calculated by water budgets. The difference was greater in Parker Valley because the winter crop data were not included.

INTRODUCTION

Purpose and Scope

In 1981 the U.S. Geological Survey established an experimental project to assess the possible and practical use of remote sensing to estimate evapotranspiration as an approximation of consumptive use of water in the lower Colorado River flood plain. The objectives of this project were (1) to evaluate various methods using remote-sensing data for identifying and measuring the areas of each vegetation type in the flood plain, (2) to identify water-use rates for each vegetation type, and (3) to estimate the total evapotranspiration of the study area.

The principal consumptive use of water in the lower Colorado River flood plain is evapotranspiration by crops. The majority of the irrigation water is diverted from the Colorado River into canals, and the rest is pumped either from wells on the mesa or directly from the river. Most of the water diverted or pumped in excess of consumptive use flows back to the river through drains, and minor amounts return as subsurface flows or direct runoff (Loeltz and Leake, 1983; Leake, 1984; Owen-Joyce, 1984). Another significant consumptive use of water in the flood plain is evapotranspiration by phreatophytes that obtain water directly from the shallow water table near the river.

Consumptive use of Colorado River water was defined by the U.S. Supreme Court (1964) as follows: "Consumptive use means diversions from the stream less such return flow thereto as is available for consumptive use in the United States or in satisfaction of the Mexican treaty obligation."

Measurements of diversions from and return flows to the Colorado River, required by the U.S. Supreme Court (1964) decree, are the responsibility of the U.S. Department of the Interior, Geological Survey (Condes de la Torre, 1982). Diversions and surface-water return flows are either measured or estimated. Subsurface return flows can only be estimated by measuring ground-water gradients and cannot be separated by source. This task has proved to be both expensive and time consuming.

Some problems of accurately calculating consumptive use within the flood plain might be alleviated if evapotranspiration could be measured or estimated directly. The problems are (1) measuring secondary diversions, (2) measuring subsurface return flows, (3) separating and crediting those return flows to the point of origin, and (4) accounting for water used by phreatophytes.

The experiment described in this report was designed to evaluate various forms of remote-sensing data for identifying and measuring areas of vegetation along the lower Colorado River. The data and analysis methods were selected on the basis of cost, availability, consistency, reproducibility, and accuracy. Areas of vegetation calculated by each method were then compared. Evapotranspiration was calculated for each method using published water-use rates for each vegetation type. These results were then compared with each other. Finally, total evapotranspiration for the study area was compared to consumptive use calculated by the water-budget method.

Five agricultural valleys—Mohave, Parker, Palo Verde, Cibola, and Yuma—lie in the Colorado River flood plain between Davis Dam and Mexico. Parker Valley (fig. 1) was selected as the principal test site for the experiment. Concurrent projects included a complete water budget for 1981 (Leake, 1984) and a comprehensive irrigation-efficiency

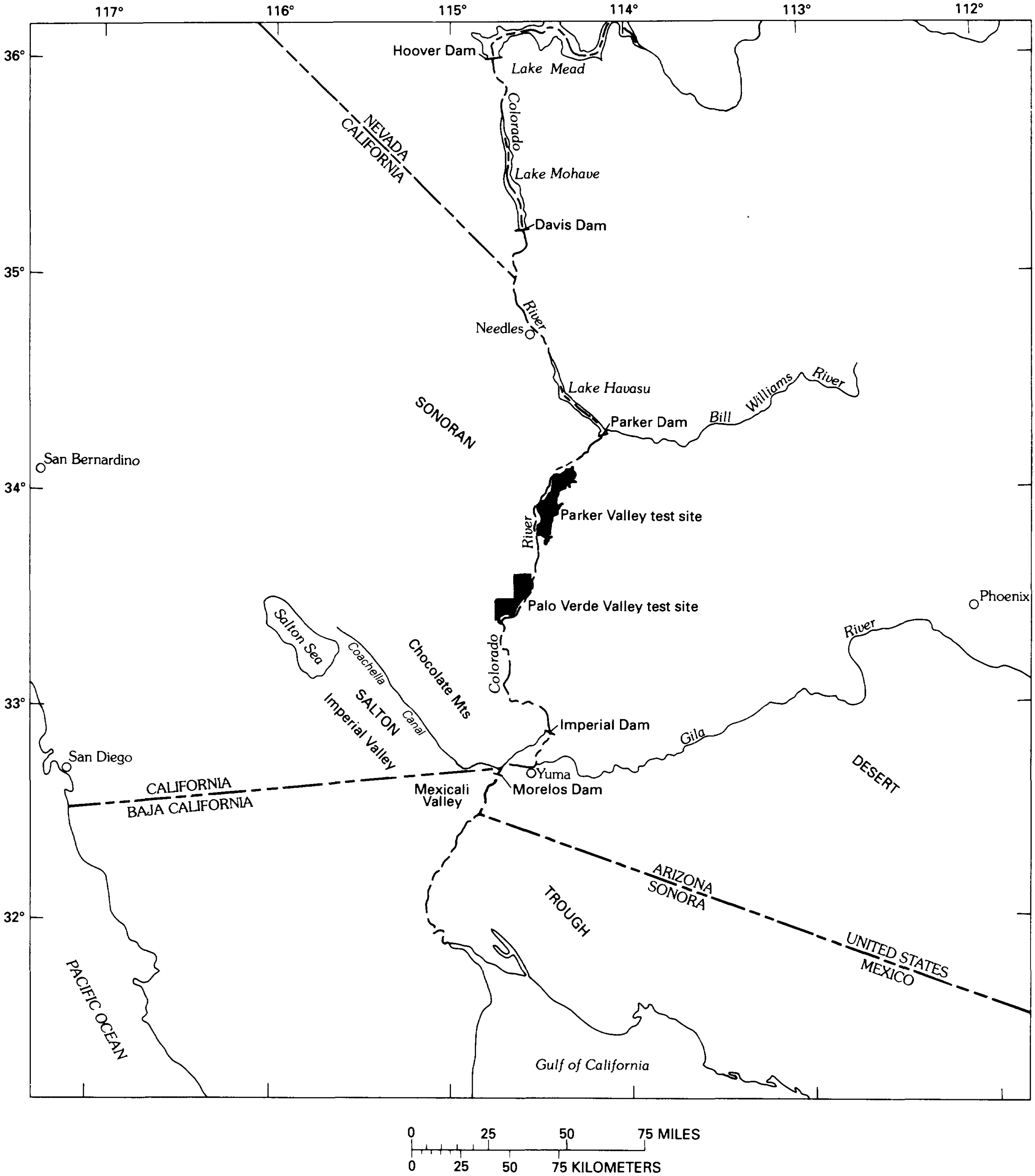


Figure 1. Area of report (shaded).

analysis (U.S. Department of Agriculture, 1985); both projects contributed data to this study. Palo Verde Valley (fig. 1) was selected as a secondary test site because of available calibration data.

Acknowledgments

The authors wish to thank all the individuals and organizations who shared their time, experience, and data during the course of this project. Herbert H. Schumann, U.S. Geological Survey, Water Resources Division, designed the original project. Paul A. Tessar, former Director of the Arizona State Land Department, Resource Analysis Division, and his staff contributed many hours of patient instruction and the use of their computer resources in the digital-analysis phase of the project. Pat S. Chavez, Jr., U.S. Geological Survey, National Mapping Division, designed an experimental procedure for vegetation classification.

The U.S. Department of Agriculture, Soil Conservation Service, Water Resources Planning Staff, Phoenix, Ariz., supplied 1981 crop data for Parker Valley. The Palo Verde Irrigation District, Blythe, Calif., supplied 1981 crop data for Palo Verde Valley. The Bureau of Indian Affairs and the Colorado River Indian Tribes shared their records and advice.

PARKER VALLEY

The primary test site was in Parker Valley, which is located approximately halfway between Davis Dam and the southerly international boundary with Mexico. The climate and crop mix are typical for the lower Colorado River flood plain. Most of the arable land is in the flood plain east of the Colorado River in Arizona. At the time the data were collected (1981–82), crops covered about 78,000 acres in this valley and phreatophytes covered about 30,000 acres.

Principal crops in Parker Valley are cotton (48 percent of the net acreage in 1981); alfalfa (33 percent); and small grains, which are mostly wheat with some barley (12 percent). Most of the remaining crops are fruits and vegetables—melons, spring and fall lettuce, and minor amounts of garlic, onions, squash, tomatoes, and milo. Multiple cropping is common in the valley. The usual combinations are spring lettuce followed by cotton, milo, melons, or fall lettuce, and wheat followed by milo, cotton, or fall lettuce. Melons may, in turn, be followed by milo or fall lettuce. Because of these cropping practices, an inventory must be taken three or four times per year to accurately identify and record all crops.

Alfalfa is actively growing from February through late November or early December. Growth is minimal during December and January, and the fields are frequently used as winter pasture for sheep. A healthy alfalfa field can be mowed as often as eight times per year and frequently more than once a month during the summer. Because fields are mowed on a rotating basis, there is a very low probability of all the fields being unmowed at the same time.

Wheat is a much more uniform crop. Wheat sprouts in November or December, ripens in late April or May, and is harvested by June. The yellow stubble may remain standing in the fields for many weeks.

Cotton—the principal summer crop—sprouts in April and is harvested in October or November. Melons sprout in February and are harvested in June. Lettuce is harvested almost continuously from late October through March. Onions grow from January through June or July.

Saltcedar (*Tamarix chinensis*), mesquite (*Prosopis* sp.), arrowweed (*Tessaria sericea*), saltbush (*Atriplex* sp.), cottonwood (*Populus fremontii*), and willow (*Salix gooddingii*) are the principal species of phreatophytes in Parker Valley (Anderson and Ohmart, 1976). These plants use ground water that, in 1981, was measured at depths ranging from 4 to 16 ft below the ground surface (Leake, 1984). They grow most densely in the abandoned meanders of the river.

Crop-Classification Methods

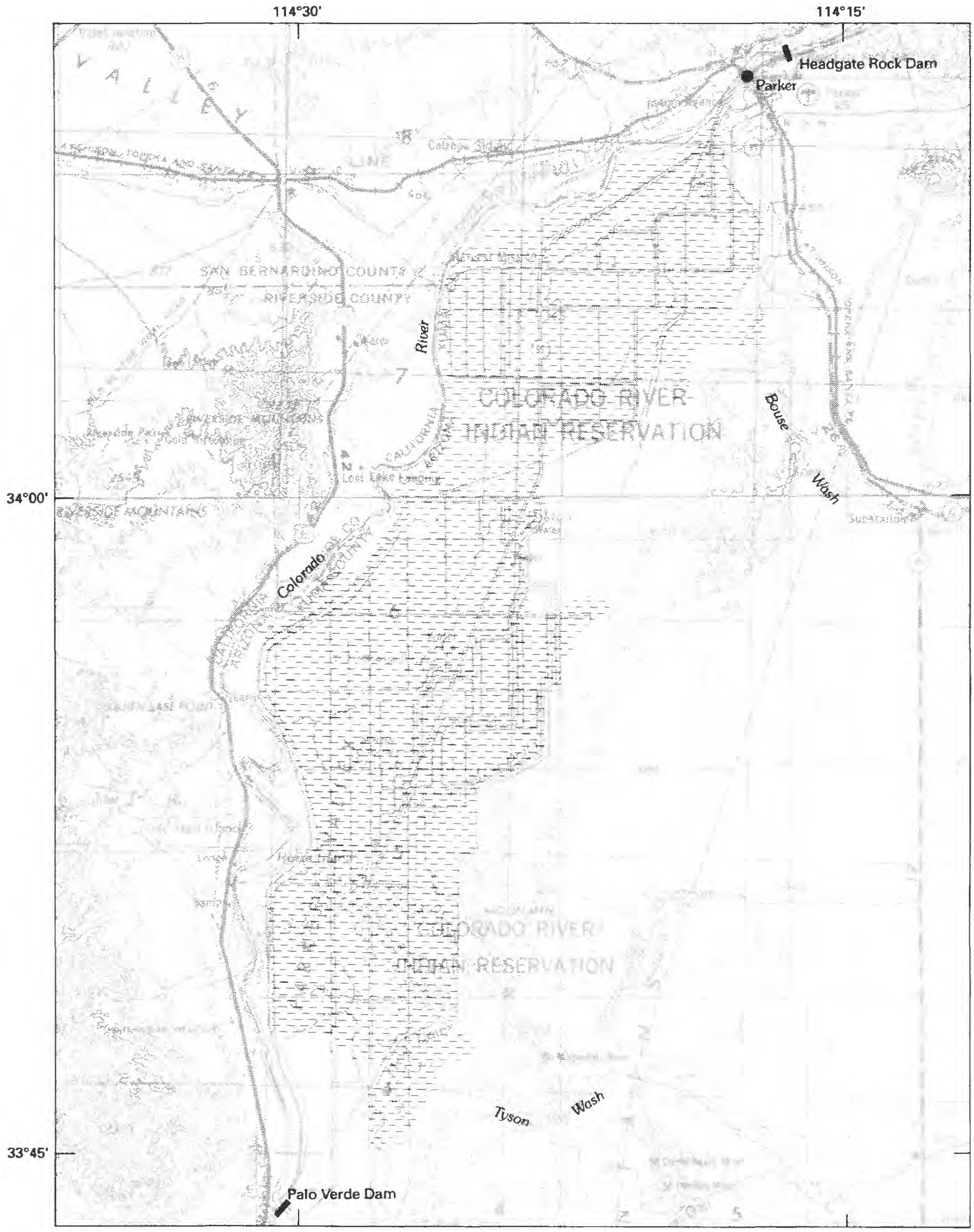
The remote-sensing data used for the crop classifications were medium-altitude (15,000–18,000 ft) aerial photography and multispectral scanner (MSS) satellite images from Landsats 2 and 3. Six remote-sensing crop-classification methods were evaluated. The results from each of the six classification methods were compared on a field-by-field basis with the corresponding crop map to determine the number of fields and acres correctly classified.

Field reconnaissance and low-altitude (less than 5,000 ft) aerial photography were used to prepare a 1982 crop map for verifying classification of the medium-altitude photography and one Landsat crop classification. The 1981 crop map, obtained from the U.S. Department of Agriculture, Soil Conservation Service, was used to verify the rest of the Landsat crop classifications. The areas of all fields in Parker Valley were digitized at a scale of 1:24,000 from orthophoto maps that had been updated from the 1982 medium-altitude aerial photography.

Approximately 85 percent of Parker Valley is included in one Landsat scene. The area on the Arizona side of the river was considered large enough (65,000 acres of crops) for a reliable comparison of the methods and was selected as the Parker Valley test site (fig. 2).

Medium-Altitude Aerial Photography

Medium-altitude color-infrared films of Parker Valley at an approximate scale of 1:32,000 were obtained for February 26, April 28, and July 10, 1982. The resolution of this photography is sufficient to identify most crops directly by their spectral differences, their density distributions



Base from U.S. Geological Survey
1:250,000 Salton Sea, 1959-69 and
Needles, 1959-69

0 5 10 MILES

0 5 10 15 KILOMETERS

CONTOUR INTERVAL 200 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

Figure 2. Parker Valley test site (patterned area).

within each cropped field, and the differences in their growing seasons.

A small area in the southeastern part of Parker Valley as it appears on each of the three films is shown in figure 3. Wheat and cotton are sensitive to soil moisture and thus to variations in soil texture. The characteristic swirling patterns in their density distributions correspond to the patterns of soil distribution in the flood plain. The gold color of senescent wheat in April is also a valuable identifying characteristic. Cotton appears dark red on infrared film in July, and wheat appears bright red on infrared film in February.

Alfalfa shows an even distribution throughout each field unless it is very young or stressed. Unmowed fields are bright red on infrared film in all seasons. Newly mowed fields have a grayish color from the drying hay, with streaks or spots of red from the sprouting alfalfa. Alfalfa can be easily misidentified, however, at certain stages of its mowing cycle. When the dry hay covers the field, even a very healthy crop can appear dead at this resolution.

In April, melon fields look like alfalfa fields on the films because of the similarity in color and ground cover. The length of the growing season is the distinguishing characteristic. The melons have been harvested by July, but alfalfa is still present. Lettuce is distinguished by its pink color on infrared film in February, and onions and garlic are distinguished by their purplish color in April.

Two visual photointerpretation methods of crop classification were tested using the medium-altitude photography. In the first method, it was noted whether or not a field had a crop on each date and, if it did, whether the crop exhibited any of the spectral characteristics discussed previously. The crops were then classified by their growing seasons and, to a lesser extent, by spectral characteristics. This approach can be used to salvage information from poor-quality films or to reduce analysis time. In the second method, a small test area of each film was calibrated by identifying each crop from the crop map and noting its spectral characteristics on the film. Each field in the rest of the test site was then compared on the three infrared films (fig. 3) and its crop identified directly. This type of identification is most useful for a small number of high-quality films or when partial cropping patterns need to be known before an entire year's data are obtained.

The results from the medium-altitude color-infrared aerial photography analyses are summarized in table 1. The classified crop type for each field in the photographs was compared with the 1982 crop map. ''Acreage classified'' is the sum of the acreages of all fields classified as a particular crop type. ''Acreage correctly classified'' is the sum of the acreages of all fields correctly classified as that crop.

The aerial photography was obtained during periods of maximum ground cover for the three major crops—cotton, alfalfa, and wheat. With the exception of lettuce, the minor crops did not have sufficient ground cover during any of the flights for an accurate classification. Lettuce was quite easy to identify because of its distinctive pink color on infrared film.

With one exception, the acreages of the major crops (and lettuce) were consistently overestimated. Crops were mistaken for each other because of similarities of apparent growing seasons or spectral characteristics. In such cases, the bias was toward the major crops because previous crop reports showed them to have the larger acreages. The exception was classification of alfalfa by growing season. As stated previously, when dry hay covers a field the crop appears dead; therefore, from the three observations, the growing season for that field tended to match that of some crop other than alfalfa.

''Percent of actual acreage that was correctly classified'' (table 1) is the ratio of the acres actually planted to a crop to the acres correctly identified as that crop. The ratio is a measure of the ability of the methods to recognize each occurrence of a given crop. Direct crop classification gave better results because spectral characteristics are necessary for separating crops with similar growing seasons.

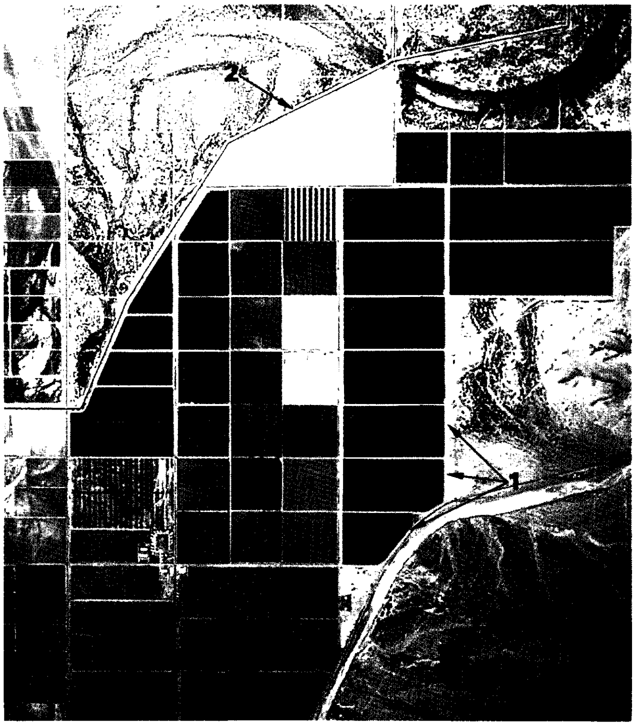
''Percent of acreage classified that was correctly classified'' is the ratio of the number of acres classified as a particular crop to the number of acres correctly identified as that crop. The ratio is a measure of the degree of misclassification inherent in each method. Neither method gave consistently better results than the other.

The column ''Lettuce/cotton'' includes fields double cropped, with lettuce planted in the winter and cotton in the summer (which is the case for most of the lettuce fields). For the direct crop-classification method, the acreage correctly classified includes fields correctly classified as lettuce in the winter and cotton in the summer. This number is included in both the ''Lettuce'' and ''Cotton'' columns under the corresponding dates. For the classification by growing season, a separate lettuce/cotton class was created. Fields classified as this combination had crops in February and July but none in April. These fields are not included in the ''Lettuce'' and ''Cotton'' columns. Several of the fields misclassified as lettuce/cotton were actually alfalfa that was mowed in April but not in February or July.

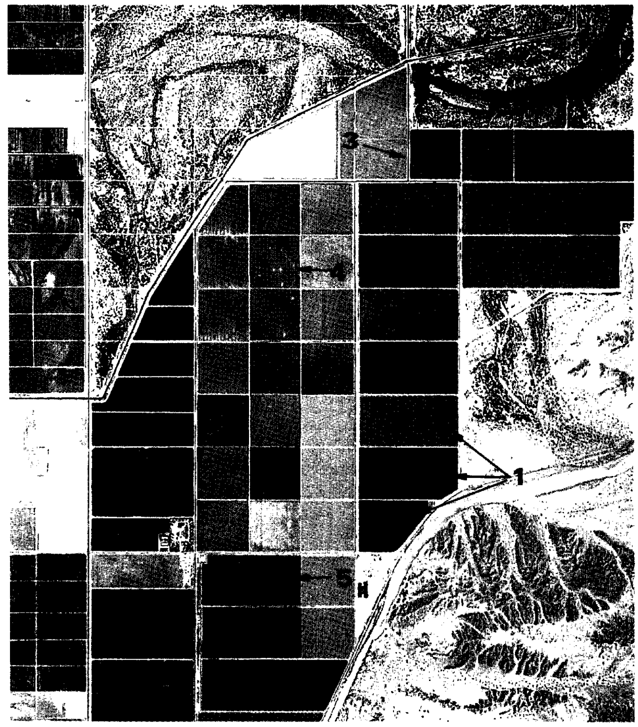
Satellite Images

Five Landsat MSS images were selected for the satellite-image analyses. The acquisition dates were February 24, March 23, May 7, July 18, and October 16, 1981. Of the images available for 1981, these dates corresponded most closely to the maximum ground cover for the major crops in Parker Valley.

The MSS scans the ground as the satellite passes over and records electromagnetic reflectance in four bands of the spectrum: one in the green, 0.4–0.5 micrometers (μm); one in the red, 0.6–0.7 μm; and two in the reflected near-infrared,



A. February 26, 1982



B. April 28, 1982

C. July 10, 1982

EXPLANATION

GROUND–COVER TYPES

1 Alfalfa–Shows changes in mowing patterns throughout the year

2 Fallow–Shows field prepared for planting

3 Wheat

4 Onions

5 Garlic

6 Tomatoes

7 Melons

8 Cotton–Shows two styles of planting

Figure 3. Medium-altitude color-infrared aerial photographs showing part of the Parker Valley test site. *A*, February 26, 1982. *B*, April 28, 1982. *C*, July 10, 1982.

Table 1. Summary of crop classification from medium-altitude color-infrared aerial photography in the Parker Valley test site, 1982

	Cotton	Alfalfa	Small grains	Melons	Lettuce	Bermuda	Onions	Fallow	Other	Lettuce/ cotton[1]
Direct crop classification:										
February										
Actual acreage	------	20,106	4,423	-----	1,419	620	338	36,347	1,708	1,344
Acreage classified	------	20,683	4,709	-----	1,499	525	0	35,467	1,078	-----
Acreage correctly classified	------	18,807	3,601	-----	1,384	434	0	34,200	147	1,059
Percent of actual acreage that was correctly classified	------	94	81	-----	98	70	---	94	9	79
Percent of acreage classified that was correctly classified	------	91	76	-----	92	83	---	96	14	-----
April										
Actual acreage	------	20,106	4,423	-----	-----	620	338	36,347	1,708	-----
Acreage classified	------	21,466	4,784	-----	-----	561	426	36,955	769	-----
Acreage correctly classified	------	18,627	3,640	-----	-----	434	270	33,140	147	-----
Percent of actual acreage that was correctly classified	------	93	82	-----	-----	70	80	91	9	-----
Percent of acreage classified that was correctly classified	------	87	76	-----	-----	77	63	90	19	-----
July										
Actual acreage	28,630	22,088	-----	3,826	-----	788	---	6,429	3,200	-----
Acreage classified	29,829	22,683	-----	2,196	-----	561	---	7,936	1,756	-----
Acreage correctly classified	26,287	20,627	-----	1,930	-----	384	---	5,595	188	-----
Percent of actual acreage that was correctly classified	92	93	-----	50	-----	49	---	87	6	-----
Percent of acreage classified that was correctly classified	88	91	-----	88	-----	68	---	71	11	-----
Classification by growing season:										
Actual acreage	27,286	22,088	4,423	3,826	75	788	338	1,887	1,562	1,344
Acreage classified	30,624	19,597	4,625	1,351	374	0	0	3,488	2,483	2,419
Acreage correctly classified	25,872	18,736	3,773	801	35	0	0	1,344	1,443	1,344
Percent of actual acreage that was correctly classified	95	85	85	21	47	---	---	71	92	100
Percent of acreage classified that was correctly classified	84	96	82	59	9	---	---	39	58	56

[1]Fields planted with lettuce in the winter and cotton in the summer.

0.7–0.8 and 0.8–1.1 μm. Each scan line is composed of elements, with each element containing the average reflectance of approximately a 1.14-acre (57 m by 57 m) area. The electromagnetic energy received by the sensor is converted to a digital number and then relayed to a receiving station on the ground. Each number corresponds to the average reflectance for one picture element (pixel) in one band of the spectrum plus error introduced by atmospheric conditions, sun elevation angle, and electronic noise. Sabins (1978) presents a detailed discussion of Landsat sensor design, operation, and applications.

Data reduction is particularly important for multitemporal digital analyses. A combination of all four bands from each of several images can exceed the capacity of the processing system. Two or more raw data bands may be mathematically combined into a single two-dimensional matrix to reduce the volume of data while preserving distinctive spectral characteristics of the ground cover.

MSS bands 5 (0.6–0.7 μm) and 7 (0.8–1.1 μm) were selected from each image for the crop classifications. Healthy vegetation absorbs red radiation and reflects near-infrared radiation (fig. 4*A*, *B*). Water, soil, rocks, and other nonvegetative ground cover reflect or absorb about the same amount of radiation in the red and near-infrared bands (fig. 4*A*, *B*). For example, in figure 4 white sand reflects a high percentage of radiation in both bands and water reflects a low percentage in both. This characteristic spectral response of vegetation compared with that of nonvegetation can be

A. *B*. *C*.

Figure 4. Landsat MSS bands and band ratio for the Parker Valley test site, July 18, 1981. *A*, Red spectral band. *B*, Near-infrared spectral band. *C*, Band 7/5 ratio with a linear stretch.

used to separate the vegetation from other types of ground cover in the image. Two crop-classification methods using Landsat multispectral images are now presented. The first method utilized the images in digital form and the second in visual (photographic) form.

Digital-Image Classification

The five Landsat MSS images were obtained in digital form on computer-compatible tape. Owing to slight variations in the satellite orbits and image geometry through time, the position of any given point on the ground also varies from image to image. The variations can be corrected by digitally registering the images to each other.

The images were displayed on a video-display terminal and common ground-control points identified. One image was arbitrarily selected as the base. The other images were then digitally registered to it by matching the pairs of ground-control points and adjusting the distances between them on the mapped image to equal those on the base image.

For each pixel in each image, the band 7 reflectance was divided by the corresponding band 5 reflectance and then multiplied by a constant, which produced a matrix of band ratios. Band-ratio techniques are discussed in detail in Taranik (1978). The resultant combination is hereafter referred to as a band 7/5 ratio. The primary purpose of the constant was to standardize the images. The actual magnitude of the constant depended on the overall brightness of each image, the amount of atmospheric haze, and other variables between the images.

An example of a band 7/5 ratio for the test area on July 18, 1981, is shown in figure 4*C*. Pixels with high band ratios (healthy vegetation) appear very bright in the image and those with low ratios (soil, rocks, water, and other nonvegetation) appear very dark because the display assigns brightness values in direct proportion to the magnitude of the numerical data.

All the digital-image classifications were made from multitemporal composites of band ratios using the maximum-likelihood classification algorithm (Graham and others, 1985, v. 2, p. A14–A17). The program groups into classes those pixels with band ratios that are less than a prescribed minimum distance from each other on all dates. Each class represents a ground-cover type with the same spectral characteristics through time. The number of classes formed is an inverse function of the minimum-distance value. If the distance is too great, dissimilar cover types may be grouped into the same class. An impractically large number of classes, however, may result from selecting a distance value that is too small.

After a classification is completed, each ground-cover class must be identified. Crops like alfalfa, with its variable mowing schedule, typically form several classes. Others, like cotton, with a relatively uniform appearance throughout its growing season, generally form only a few classes. A crop map from a representative subarea of the test site was used to identify and separate the various crop classes from each other and from other vegetation classes, particularly those with the same growing seasons. All fields in the test site that formed a particular class were assumed to be the crop that was represented by that class in the calibration subarea. Each class was then color coded using image processing/display techniques to produce the final crop maps.

Three multitemporal composites of band ratios covering the Parker Valley test site were classified. Results of these classifications are presented in figure 5. The composites of dates were (1) March 23, May 7, and July 18; (2) March 23 and July 18; and (3) February 24, March 23, May 7, July 18, and October 16. These composites were selected using a crop-distribution calendar to classify the major crops—cotton, alfalfa, and small grains. Other possible composites of dates might be selected to classify different crops.

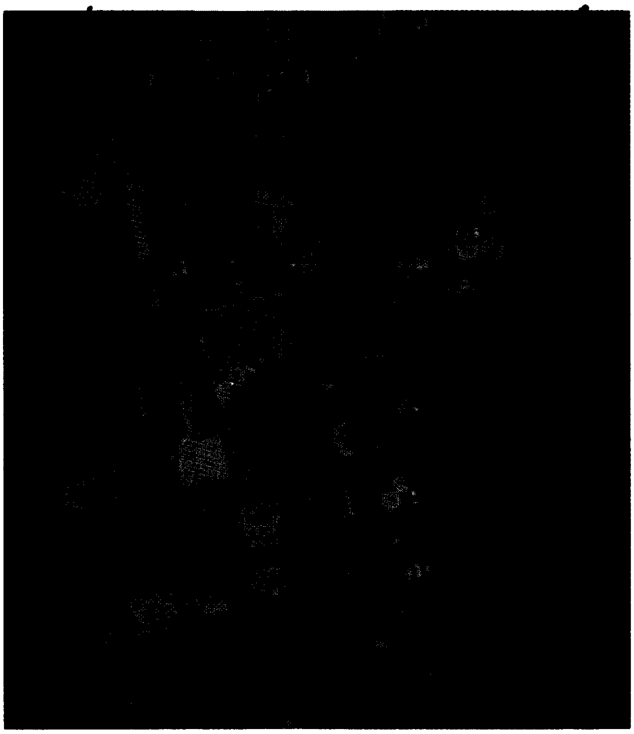
The only combination of dates to satisfactorily classify cotton, alfalfa, small grains, and melons was March, May, and July (fig. 5*A*). The classification program generated 22 classes—8 were alfalfa, 2 were cotton, 1 was small grains, 1 was melons, and 10 were water, soil, rocks, phreatophytes, or pixels that included more than one cover type.

Principal causes for misidentification of crops were the variable mowing schedules of alfalfa, densities of crop cover within a field, variations in planting and harvesting times within crop types, and amount of soil moisture in fields with less than 100 percent ground cover. The distribution density of cotton varied widely; many acres of sparse cotton were classified as bare soil. Many acres of melons also were classified as bare soil because the crop cover was not dense enough in May to register on the images; furthermore, this crop was harvested by July. A June image would have been better than a May image for melons. Many of the small grains, however, would have been harvested before June and thus would not have appeared on that image.

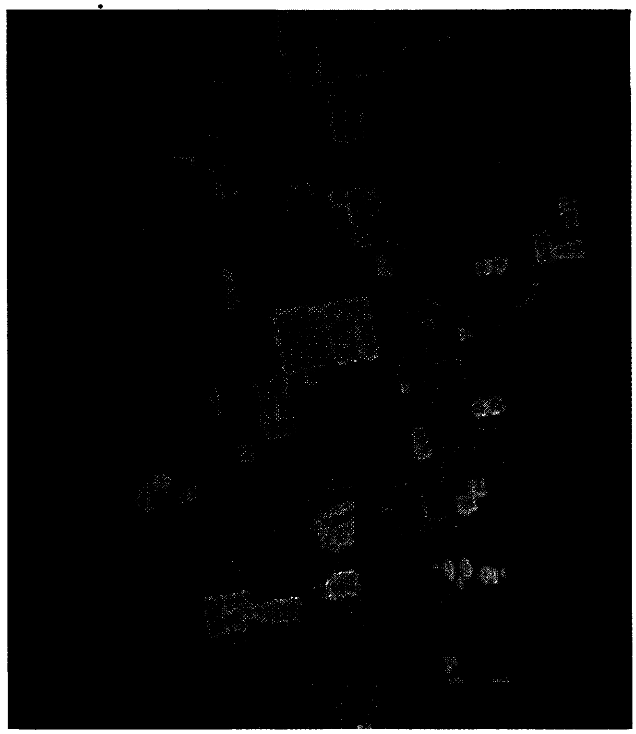
Results from the classification of the two-date composite of March and July (fig. 5*B*) were as good for the three major crops as were those from the three-date composite. Less actual crop acreage was classified as bare soil than in the three-date classification. Misclassification of alfalfa with small grains increased slightly; some small grains resembled alfalfa that was unmowed in March and mowed in July. Melons have insufficient ground cover in March to be visible at MSS resolution.

The cost of obtaining raw data and the time required for analysis are less for a two-date classification than for a three-date classification. The two-date classification is sufficient for separating two or three major crops from each other and from the remaining ground cover. The dates, however, must be carefully selected to reflect differences in growing seasons in addition to spectral differences.

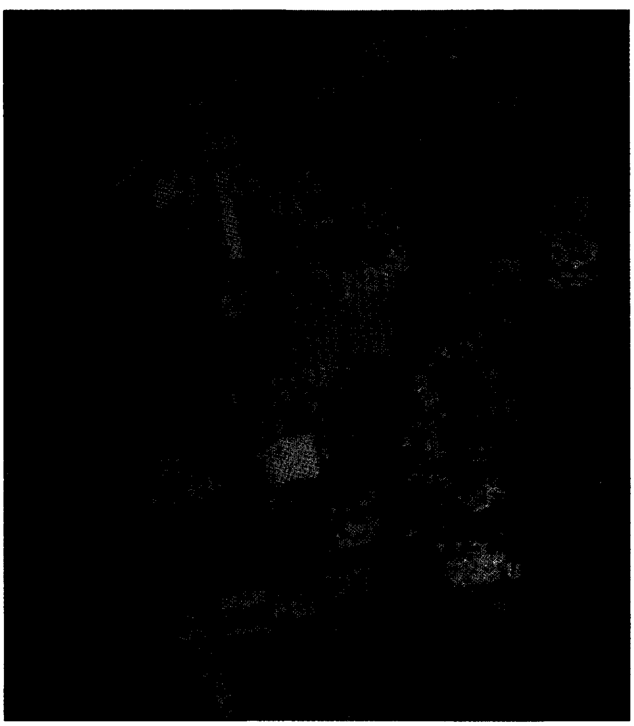
Least successful was the five-date classification using February, March, May, July, and October (fig. 5*C*). Theoretically, this approach should have supplied the necessary



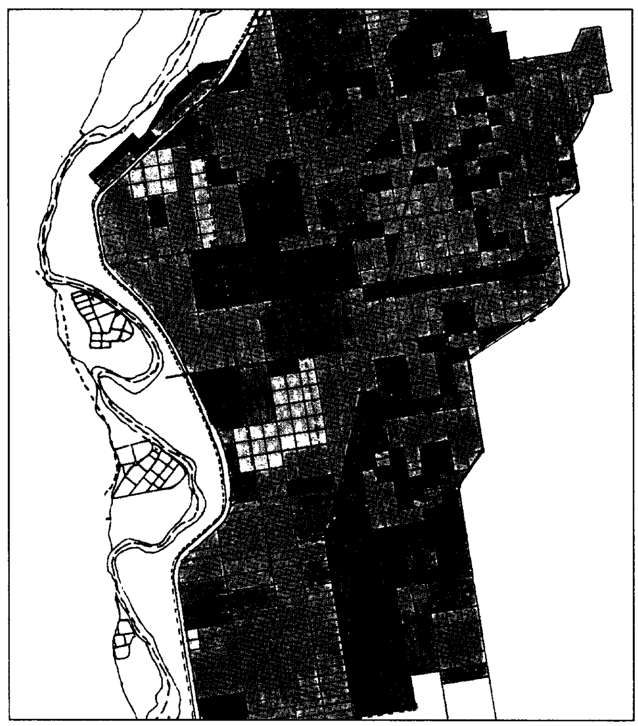
A. March, May, and July 1981



B. March and July 1981



C. February, March, May, July, and October 1981



D. Hand-colored crop map from the U.S. Department of Agriculture (1985)

Figure 5. Video displays of crop classification from Landsat digital satellite data for part of the Parker Valley test site. *A,* March, May, and July 1981. *B,* March and July 1981. *C,* February, March, May, July, and October 1981. *D,* Hand-colored crop map prepared from a field check of the area (from the U.S. Department of Agriculture, 1985).

data to classify the minor crops as well as the major ones. Instead, the complexity of the data caused misclassification, especially between small grains and alfalfa, alfalfa and double-cropped lettuce and cotton, and melons and phreatophytes.

Results of the two-date and three-date classifications are summarized in table 2. The five-date classification was too poor to be calibrated.

Differences between the results of the two digital methods are slight and inconclusive. In both cases, classifications of cotton and small grains were slightly poorer than those for the methods involving aerial photography, but fewer acres of other crops were classifed as cotton or small grains. Misclassification of alfalfa was greater for the digital methods. Classification of melons was better for the three-date digital-image method than for the aerial-photography methods. Even though May is not the optimum month for classifying melons, it is better than April.

Visual Photointerpretation of Landsat Satellite Images

Landsat images can also be obtained in photographic form. Black-and-white transparencies of the red band 5 (0.6–0.7 μm) and near-infrared band 7 (0.8–1.1 μm) were overlaid to form a composite image for each of the five image dates previously discussed. An additional image (December 18, 1980) was used to obtain more data for alfalfa and lettuce. For each date, each field was coded as vegetated or nonvegetated onto a transparent overlay of the field boundaries. Crops were identified only by their growing season.

The analysis was repeated for 1982 images because the 1981 crop map did not include winter-crop information. The image dates selected were February 1, April 23, May 29, June 16, and August 9, 1982. The June image provided additional data for melons.

Results of these classifications are summarized in table 3. All crop classifications from visual analysis were more accurate in 1982 than in 1981. April and August data reflect denser ground cover for wheat and cotton, respectively, than do March and July data. Lettuce apparently has insufficient ground cover in February to register well on Landsat images. Because visual-image classification requires considerable subjective judgment, the experience gained during the 1981 classification undoubtedly contributed to the improved results of the 1982 classification. Results were consistently better for the 1982 classification than for any other classification in the experiment.

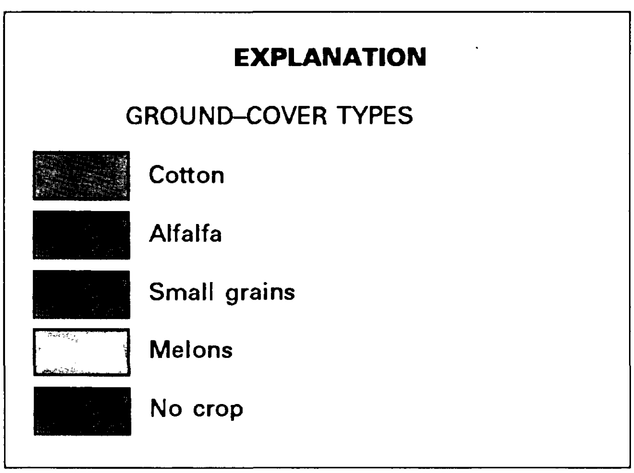


Figure 5. Continued.

Evapotranspiration by Crops

In Parker Valley, water applied to fields in excess of evapotranspiration by vegetation returns to the river by surface or subsurface flow and is available for reuse (Leake, 1984). Consumptive use in agricultural areas may be defined as the sum of evapotranspiration by vegetation plus the surface evaporation from open water or bare soil.

Evapotranspiration by crops has been studied by the U.S. Department of Agriculture at their experimental station near Phoenix, Arizona. Erie and others (1965) have published water-use rates for each of the major Arizona crops (table 4). These rates were adjusted for climatic conditions that approximate those of Parker Valley by applying the formula developed by Blaney and Criddle (1962) and using climatic data from Yuma, Arizona (H.C. Millsaps, U.S. Department of Agriculture, written commun., 1982). The adjusted values are given as the second set of data in table 4.

The U.S. Department of Agriculture, Soil Conservation Service, made detailed measurements of evapotranspiration by cotton, alfalfa, and wheat in Parker Valley during 1980–82 as part of their irrigation-efficiency study (U.S. Department of Agriculture, 1985). The figures for alfalfa and small grains as shown in table 4 differ by about 0.2 acre-ft from those estimated by the Blaney-Criddle formula.

Evapotranspiration calculations for this study utilized Soil Conservation Service field data for cotton, alfalfa, and small grains. Blaney-Criddle figures were used for the minor crops because better estimates were not available at that time. The classification "other" (tables 1–3) was assigned an arbitrary water-use rate of 2.0 acre-ft, which represents the average water-use rate of all the minor crops.

Evapotranspiration by crops in the Parker Valley test site was calculated as the sum of the acreages of each crop from the crop maps multiplied by the respective water-use rates. This was the standard to which evapotranspiration estimates from the various remote-sensing methods were compared. The standard was 235,062 acre-ft in 1981 and 231,209 acre-ft in 1982.

For each of the six classification methods, evapotranspiration estimates were evaluated as follows:

1. The number of acres classified for a particular crop was multiplied by the water-use rate for that crop.
2. The remaining irrigated acreage was classified as "other" and multiplied by 2.0 acre-ft.

Table 2. Summary of crop classifications from Landsat digital satellite images in the Parker Valley test site, 1981

	Cotton	Alfalfa	Small grains	Melons	Fallow	Other
Actual acreage:	31,178	21,642	7,824	1,812	1,002	1,503
Three-date classification:						
Acreage classified	28,690	23,325	5,622	1,201	0	6,123
Acreage correctly classified	27,392	19,185	5,069	1,129	0	0
Percent of actual acreage that was correctly classified	88	89	65	62	-----	-----
Percent of acreage classified that was correctly classified	95	82	90	94	-----	-----
Two-date classification:						
Acreage classified	30,450	23,062	5,999	0	0	5,450
Acreage correctly classified	28,135	18,898	5,576	0	0	0
Percent of actual acreage that was correctly classified	90	87	71	-----	-----	-----
Percent of acreage classified that was correctly classified	92	82	93	-----	-----	-----

3. Results were summed to get a total evapotranspiration estimate.
4. The total evapotranspiration estimate was divided by the standard to compare the relative effectiveness of the methods.

Results are presented in table 5.

All the evapotranspiration estimates are within ±3 percent of the standards. The highest estimates of evapotranspiration are from the digital-image classifications, which had more acreage classified as alfalfa and cotton than did the other methods. Alfalfa uses nearly three times as much water as cotton and almost twice as much as small grains. Correct identification of alfalfa and cotton, therefore, is more important to the accuracy of the evapotranspiration estimate than that of any other crops in this area.

Phreatophytes

Anderson and Ohmart (1976) mapped phreatophytes in the Colorado River flood plain by species and by stand structure. For this experiment, copies of their maps were updated using the 1982 aerial photography. Phreatophytes were grouped into four classes by percentage of ground cover (0–25, 26–50, 51–75, and 76–100 percent). The areas of each cover class and of each species were then digitized from the maps.

Phreatophytes accounted for about 28 percent of all the vegetation in the Parker Valley test site in 1981 and 1982. Many experimental projects have been designed to estimate the amount of water used by phreatophytes. Anderson (1976) gives a summary of the experimental work. Although the results vary widely, most authors agree that evapotranspiration for dense stands of most species is as high or higher than that of crops in the same area. Evapotranspiration by phreatophytes, therefore, is an important component of consumptive use of water in Parker Valley.

Most of the experimental work on evapotranspiration by phreatophytes has been done for pure stands under controlled conditions. Under natural conditions, the amount of water used by these plants depends on climate, on depth and salinity of ground water, and on rooting depth, density, stand composition, and stage of growth or activity of the plants. For these reasons, the results of experimental work are difficult to apply under field conditions.

Two approaches that are based on field studies were selected to estimate evapotranspiration by phreatophytes in Parker Valley. The results are compared in table 6. In one appoach, Culler and others (1982) concluded that evapotranspiration by phreatophytes is primarily a function of stand density rather than species distribution. For areas of 100 percent phreatophyte density, the maximum water-use rate was 45 in./yr and the minimum for areas of no phreatophyte cover was 14 in./yr.

Table 3. Summary of crop classifications from visual photointerpretation of Landsat images in the Parker Valley test site

	Cotton	Alfalfa	Small grains	Melons	Lettuce	Fallow	Other
		1981					
Actual acreage	31,178	21,642	7,824	1,812	Unknown	1,002	1,503
Acreage classified	27,000	24,090	4,305	788	107	1,650	7,020
Acreage correctly classified	25,621	19,123	3,876	679	-----	429	-----
Percent of actual acreage that was correctly classified	82	88	50	37	-----	43	-----
Percent of acreage classified that was correctly classified	95	79	90	86	-----	26	-----
		1982					
Actual acreage	28,630	22,088	4,423	3,826	1,419	1,887	2,668
Acreage classified	26,863	22,380	4,598	5,107	120	4,057	1,836
Acreage correctly classified	25,792	20,791	4,125	3,295	0	1,301	1,794
Percent of actual acreage that was correctly classified	90	94	93	86	-----	69	67
Percent of acreage classified that was correctly classified	96	93	90	65	-----	32	98

Another approach was taken by the Boyle Engineering Corporation (1976) for their salinity-control study in Parker Valley. They used optimum water-use rates developed for each species in the lower Colorado River flood plain by the U.S. Bureau of Reclamation and adjusted them for the stand densities in Parker and Palo Verde Valleys.

Water-use rates developed by these two approaches were applied to the species and stand-density classes digitized from the maps in Parker Valley. The range of water-use rates from Culler and others (1982) was divided into four ranges corresponding to the four cover classes. The average value for each range was multiplied by the number of acres in the class. For the Boyle approach, the acreage of each species obtained from the updated maps was multiplied by the average water-use rate developed for that species.

The evapotranspiration estimate for phreatophytes calculated by the Culler approach was 6 percent lower than that calculated by the Boyle approach. The Boyle approach, which was developed in and for Parker Valley, was selected for this study.

Water Budget

Leake (1984) prepared a water budget for 1981 for the entire Parker Valley. He was able to measure or estimate all surface-water and ground-water diversions and return flows, tributary and ground-water inflow and outflow, precipitation, and open-water evaporation. The residual term in this budget was consumptive use. The crop map for the entire valley east of the river was used to compare evapotranspiration estimates with consumptive use calculated by the water-budget method. Consumptive use in Parker Valley as calculated from the water budget developed by Leake was 392,100 acre-ft. Evapotranspiration calculated from the complete Parker Valley crop map and the phreatophyte maps was 327,000 acre-ft; the difference (65,100 acre-ft, or 17 percent) is due in part to lack of information about evaporation from bare soil (Leake, 1984, p. 25). Some fallow fields in Parker Valley are irrigated to preserve soil texture and leach out salts. This evaporation term is extremely difficult to estimate and was not included in the evapotranspiration calculations made from the crop map. Another contributing factor to the difference is the absence of winter crops—particularly lettuce—from the 1981 crop map.

PALO VERDE VALLEY

Subsequent to the Parker Valley analysis, a crop classification was made for a part of Palo Verde Valley (fig. 6) using only the three-date digital-image method. The purpose of the classification was to verify the accuracy of the method in another area where a more complete crop map for 1981 was available.

Table 4. Water-use rates, in acre-feet, for crops in southern Arizona

	Cotton	Alfalfa	Small grains	Melons	Lettuce	Bermuda	Onions	Citrus (oranges)
Rates derived from:								
Erie and others (1965)	3.6	6.4	2.2	1.8	0.7	3.8	1.9	3.2
Blaney-Criddle formula[1] (H.C. Millsaps, U.S. Department of Agriculture, written commun., 1982)	3.2	5.5	1.7	1.5	0.7	4.6	---	3.9
U.S. Department of Agriculture (1985)	3.2	5.3	1.9	---	---	---	---	---

[1]Adjusted.

Palo Verde Valley lies south and slightly west of Parker Valley. The climate and cropping practices are similar, although a greater variety of fruits and vegetables are grown in Palo Verde Valley than in Parker Valley. The most important of these in the test site were citrus orchards and tomatoes. The valley has about 92,000 acres in crops and 6,900 acres in phreatophytes.

Crop Classification

The crop classification in Palo Verde Valley utilized the same three image dates—March 23, May 7, and July 18, 1981—as did the Parker Valley classification. Results of this classification are presented in table 7. Unlike the Parker Valley crop map, the Palo Verde Valley map did include winter crops, which permitted calibration of double-cropped lettuce and cotton.

The three-date classification in Palo Verde Valley was slightly more accurate overall than that in Parker Valley. A higher percentage of melon acreage was identified, but a higher percentage of other crops was misidentified as melons. Accuracy of the lettuce/cotton classification was similar to that of melons.

Palo Verde Valley had more crops with similar growing seasons than did Parker Valley. In two cases, the classification program grouped such crops together: tomatoes with melons, and citrus trees with alfalfa. The combined acreage of tomatoes and citrus is less than 2 percent of the total crop acreage in the test site. In other areas where these crops are more common, however, misclassification could have a significant effect on results.

Evapotranspiration by Crops

Evapotranspiration by crops in the Palo Verde Valley test site estimated from digital-image analysis was 165,191 acre-ft. Evapotranspiration calculated from the crop map was 167,210 acre-ft, a difference of 1 percent. The accuracy of the evapotranspiration estimate depends on the acreage classified as a particular crop. The acreages classified were closer to the true acreages for the corresponding crops in Palo Verde Valley than in Parker Valley—particularly for cotton and alfalfa, which are the major crops. The high water-use rate of alfalfa compared with that of other crops means that fluctuations in its acreage have more effect on total evapotranspiration than do water-use rates of other crops. Alfalfa constituted 28 percent of the total test-site acreage in Palo Verde Valley compared with 33 percent in Parker Valley. The effect of estimating alfalfa acreage correctly was therefore slightly reduced in Palo Verde Valley.

Because of the dates selected (March, May, and July), the images cannot include any crops planted after July and harvested before March. The only such crop with significant acreage in the Palo Verde Valley test site was fall lettuce. Evapotranspiration by fall lettuce as calculated using the crop map was slightly less than 1 percent of the total evapotranspiration. In areas where evapotranspiration by fall crops is significant, a fall image should be included in the analysis.

Water Budget

A water budget for 1981 was prepared for Palo Verde Valley by Owen-Joyce (1984) utilizing an approach similar

Table 5. Evapotranspiration by crops in the Parker Valley test site

	Evapotranspiration, in acre-feet		
	Standard	Estimated	Percentage of standard
Aerial photography (1982):			
Classification by crop type[1]	231,209	229,065	99
Classification by growing season	231,209	227,337	98
MSS digital data (1981):			
Two-date	235,062	241,967	103
Three-date	235,062	240,160	102
MSS photointerpretation:			
1981	235,062	237,557	101
1982	231,209	224,728	97

[1]For crops classified on two or three films, the arithmetic-mean acreage was used to calculate evapotranspiration.

Table 6. Evapotranspiration by phreatophytes in the Parker Valley test site

	Water use, in feet per year	Area, in acres	Evapotranspiration, in acre-feet per year
Ground cover, in percent[1]			
0-25	1.5	9,908	14,862
26-50	2.1	9,331	19,595
51-75	2.8	3,265	9,142
76-100	3.4	5,437	18,486
Total		27,941	62,085
Species[2]			
Saltcedar	3.9	3,767	14,691
Arrowweed	2.2	6,000	13,200
Mesquite	1.9	11,031	20,959
Cottonwood-willow	3.9	1,481	5,776
Mixed stand	2.0	5,662	11,324
Total		27,941	65,950

[1]Culler and others (1982).
[2]Boyle Engineering Company (1977).

to that of Leake (1984). The residual term in this budget was also consumptive use.

Consumptive use calculated from the water budget developed by Owen-Joyce for the part of the valley drained by drainage ditches was 451,900 acre-ft. Evapotranspiration calculated from the Palo Verde Valley crop map and phreatophyte map was 403,800 acre-ft—a difference of 48,100 acre-ft, or 11 percent. Owen-Joyce (1984, p. 29) states that the most probable reason for the discrepancy is unmeasured evaporation from open water and bare soil. Evapotranspiration estimates from the crop-classification method were closer to the consumptive-use estimates made by the water-budget method in Palo Verde Valley than in Parker Valley. One important reason is the inclusion of winter crops in the Palo Verde Valley map.

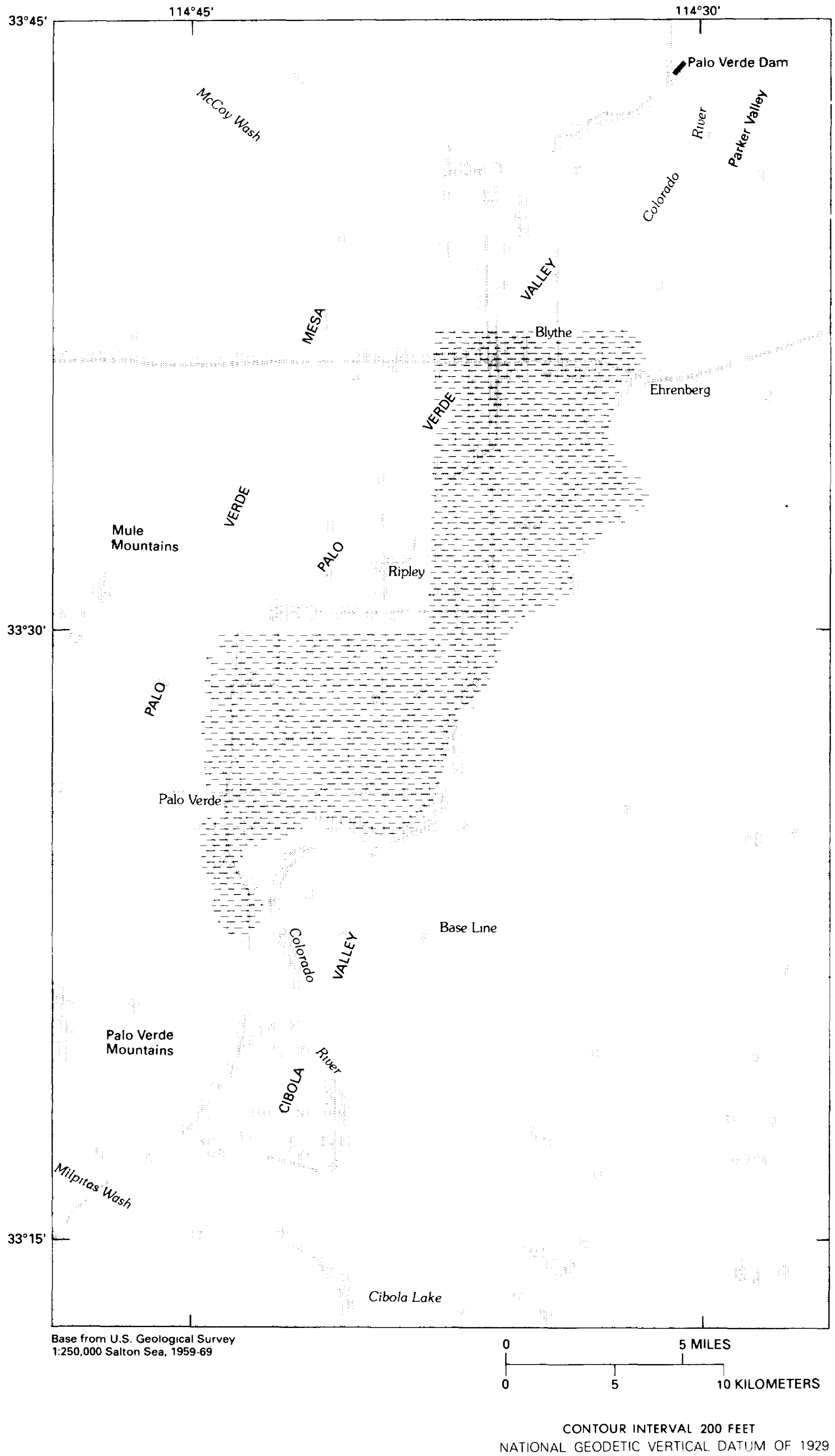


Figure 6. Palo Verde Valley test site (patterned area).

Table 7. Summary of crop classificatons from Landsat digital satellite images in the Palo Verde Valley test site, 1981

	Cotton	Alfalfa	Small grains	Melons	Tomatoes	Citrus	Bermuda	Lettuce	Fallow	Other	Small grains/ cotton[1]	Lettuce/ cotton[1]
Actual acreage	14,366	12,925	4,002	4,655	387	431	544	157	239	3,423	3,799	1,806
Acreage classified	14,369	[2]13,523	6,470	[3]4,009	0	0	0	0	0	3,752	3,121	1,490
Acreage correctly classified	13,260	10,791	3,112	3,324	[4]387	[5]298	0	0	0	2,075	1,244	1,244
Percent of actual acreage that was correctly classified	92	83	78	71	---	---	---	---	---	61	33	69
Percent of acreage classified that was correctly classified	92	80	48	83	---	---	---	---	---	55	40	83

[1]Fields planted with small grains or lettuce in the winter and cotton in the summer.
[2]Alfalfa or citrus.
[3]Melons or tomatoes.
[4]Tomatoes misclassified as melons.
[5]Citrus misclassified as alfalfa.

DISCUSSION

Comparison of Methods

On the basis of the foregoing analyses, evapotranspiration can be estimated by using various classification and processing methods on remote-sensing data and water-use rates developed in the field. Selection of the optimum data set and method for a particular project depends on the size of the project area, the degree of accuracy required, and the type of labor and equipment.

No method gives error-free results. Even field reconnaissance is subject to errors of observation and transcription. In addition, agricultural practices vary. A particular field may be abandoned or replanted after the observation is made. Field reconnaissance yields the most accurate crop identifications but is very time consuming. Used with some spot checking on the ground, low-altitude aerial photography is nearly as accurate and is much faster than field reconnaissance because it allows easy access to remote areas. Neither method is practical for making an annual inventory and acreage calculation for crops in an area the size of the lower Colorado River flood plain.

The best classification of lettuce was from medium-altitude aerial photography. Interpretation of aerial photography and photointerpretation of Landsat images are good methods for classifying minor crops, such as lettuce and melons, if image dates are selected for maximum ground cover of these species.

Of the eight classification methods used, visual photointerpretation of Landsat images had the lowest cost for obtaining and analyzing data for Parker and Palo Verde Valleys. Aerial photography had the highest cost for obtaining and analyzing data. Digital-image analysis is intermediate in cost if the necessary computer facilities are available; otherwise, image-processing costs must be included.

Analyses of aerial photography and photointerpretation of Landsat images require considerable subjective judgment. If the same analyses are performed by different individuals, results can vary. The digital-image analyses require little subjective judgment, and results can be reproduced with greater precision.

Visual photointerpretation of Landsat images is a quick and inexpensive way to map crops in a few fields but is much too slow for large areas. Aerial photography is particularly good for precise identification in small areas but has the same problems as visual photointerpretation, in addition to a higher acquisition cost. For the lower Colorado River flood plain, satisfactory results for the most reasonable investment in time, labor, and cost were obtained from digital-image analysis.

Evapotranspiration estimates in this study were good because regional water-use rates for crops in this area have been established by field studies and because the test sites were large enough for the average water-use rates at the sites to approach the regional averages. This method would not be as reliable in areas where (1) regional water-use rates are not well known or (2) the average evapotranspiration in the study site is not known and differs from the regional average. For these cases, water-use rates must first be established by methods such as soil-moisture depletion, energy budgets, or water budgets.

Evaluation of Evapotranspiration Estimates

The acreage correctly classified averaged 84 ± 11 percent of the actual acreage for the major crops and 64 ± 27 percent for the minor crops. The acreage correctly classified averaged 86 ± 10 percent of the acreage classified for the major crops and 59 ± 28 percent for the minor crops. All the evapotranspiration estimates, however, were within ± 3 percent of evapotranspiration calculated from the respective crop maps.

These results indicate that evapotranspiration calculated from crop mapping using remote-sensing data is relatively insensitive to actual crop classification regardless of the method employed. Probable reasons are the following:

1. Total acreage remains constant; acreage not classified as specific crops is classified as "other."
2. Water-use rates for crops most often misclassified (such as bermuda, citrus, or lettuce/cotton with alfalfa) are similar.
3. The average annual evapotranspiration for all crops studied (regardless of the acreage) was 2.2 ft compared with 2.0 ft for the class "other."
4. No disproportionate misclassification of crops with high or low water-use rates occurred; therefore, the classification errors tended to cancel each other.

All the crop-classification methods tested using remote-sensing data gave evapotranspiration estimates that closely approximated each other.

Leake (1984) and Owen-Joyce (1984) suggested evaporation from bare soil and lack of data on winter crops as probable reasons for the discrepancies between evapotranspiration calculated by the crop-mapping methods and consumptive use calculated by the water-budget method. Another possible reason is variability of evapotranspiration by the same crop over areas as large and diverse as Parker and Palo Verde Valleys.

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SELECTED SERIES OF U.S. GEOLOGICAL SURVEY PUBLICATIONS

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Earthquakes & Volcanoes (issued bimonthly).
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Technical Books and Reports

Professional Papers are mainly comprehensive scientific reports of wide and lasting interest and importance to professional scientists and engineers. Included are reports on the results of resource studies and of topographic, hydrologic, and geologic investigations. They also include collections of related papers addressing different aspects of a single scientific topic.

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