MAPPING IRRIGATED CROPLAND FROM LANDSAT DATA FOR DETERMINATION OF WATER USE FROM THE HIGH PLAINS AQUIFER IN PARTS OF COLORADO, KANSAS, NEBRASKA, NEW MEXICO, OKLAHOMA, SOUTH DAKOTA, TEXAS, AND WYOMING

REGIONAL AQUIFER-SYSTEM ANALYSIS

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1400–C

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By GAIL P. THELIN *and* FREDERICK J. HEIMES

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FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The Regional Aquifer-System Analysis (RASA) Program was started in 1978 after a congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States. The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems which, in aggregate, underlie much of the country and which represent important components of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system, and accordingly transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies, both to develop an understanding of the natural, undisturbed hydrologic system, and of any changes brought about by human activities, as well as to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number, and where the volume of interpretive material warrants, separate topical chapters that consider the principal elements of the investigation may be published. The series of RASA interpretive reports begins with Professional Paper 1400 and thereafter will continue in numerical sequence as the interpretive products of subsequent studies become available.

Dallas L. Peck
Director

PREFACE

The High Plains RASA was begun in 1978 to describe the geohydrology of the High Plains aquifer and to develop a ground-water flow model of the aquifer (Weeks, 1978). Maps of irrigated cropland, compiled from Landsat-satellite data, were combined with sampled information on ground-water withdrawals for irrigation to estimate ground-water pumpage which is an integral component in the ground-water flow model.

The National Aeronautics and Space Administration (NASA) provided financial and technical support for the analysis of Landsat data through its Applications Pilot Test Program. Additional technical support for the study was provided by the University of Kansas, Kansas Applied Remote Sensing program, Informatics General Corp., and Technicolor Government Services, Inc. Valuable information was also provided by many State and local agencies throughout the High Plains.

The following individuals deserve recognition for their specific contributions to this study. Carol S. Mladinich of Technicolor Government Services, Inc. was the principal analyst responsible for the processing and interpretation of the 59 Landsat scenes required to map irrigated cropland for 1980. Walter E. Donovan of Informatics General Corp. designed and implemented innovative software which was essential to the successful completion of this project. Donald H. Card of NASA-Ames Research Center developed the sample design and supervised the analysis and interpretation of data for the accuracy evaluation conducted as part of the 1980 mapping of irrigated cropland.

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CONVERSION TABLE

Multiply inch-pound units	By	To obtain metric units
inch (in.)	2.54×10^{1}	millimeter
mile (mi)	1.609	kilometer
acre	4.047×10^{-1}	square hectometer
acre-foot (acre-ft)	1,234	cubic hectometer
square mile (mi^2)	2.59	square kilometer

To convert from degrees Celsius to degrees Fahrenheit, multiply by 1.8 and then add 32.

MAPPING IRRIGATED CROPLAND FROM LANDSAT DATA FOR DETERMINATION OF WATER USE FROM THE HIGH PLAINS AQUIFER IN PARTS OF COLORADO, KANSAS, NEBRASKA, NEW MEXICO, OKLAHOMA, SOUTH DAKOTA, TEXAS, AND WYOMING

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ABSTRACT

Landsat multispectral-scanner data have been used to map irrigated cropland for determination of water use from the High Plains aquifer. Water-use estimates have provided one critical element in a ground-water flow model being developed by the U.S. Geological Survey. Information on irrigated acreage and water use is needed to evaluate the effects of agricultural development on the High Plains aquifer. The High Plains aquifer is the primary source of water for one of the Nation's major agricultural areas covering about 174,000 square miles within parts of eight States.

Several methods for determining irrigated acreage were evaluated. Digital analysis of Landsat data proved to be the most suitable approach and was used in a two-phase effort to map irrigated acreage for both the 1978 and 1980 growing seasons. The first phase, a test of analysis procedures, used 1978 Landsat data to map the majority of the High Plains. The test used a cluster-analysis technique to derive acreage estimates of irrigated cropland, nonirrigated cropland, and rangeland using 35 summer Landsat scenes. Based on the first-phase test results, several modifications were made to streamline and improve analysis techniques for the second-phase mapping of irrigated cropland using 1980 Landsat data. The analysis of 1980 data used a ratio technique to analyze the 59 spring and summer Landsat scenes required to provide acreage estimates for the major irrigated crops on the High Plains.

Acreage estimates of irrigated cropland, nonirrigated cropland, and rangeland were aggregated to form a data base containing about 174,000 grid cells measuring 1 minute of latitude by 1 minute of longitude. Percentages for each land-use type were calculated and combined with sampled irrigation-application rates to compute estimates of irrigation water use for the ground-water flow model. An estimated 17,980,000 acre-feet of ground water was pumped from the High Plains aquifer during the 1980 growing season to irrigate 13,700,000 acres.

To verify the reliability of the irrigated-acreage estimates used to calculate water use, an accuracy evaluation was conducted for the 1980 mapping of irrigated cropland using a multistage random-sampling method. The statistical evaluation confirmed that Landsat data and simple analysis techniques can provide an efficient tool for mapping irrigated cropland for the High Plains. However, availability of suitable Landsat scenes is required to provide a complete inventory of irrigated cropland. The techniques used to map irrigated cropland for the High Plains should be applicable to similar areas of the Western United States.

INTRODUCTION

The U.S. Geological Survey began a regional study of the High Plains aquifer in 1978 as part of its Regional Aquifer-System Analysis (RASA) program. The general purpose of the High Plains RASA is to provide (1) hydrologic information needed to evaluate the effects of continued ground-water development and (2) ground-water flow models to evaluate aquifer response to changes in ground-water development (Weeks, 1978).

Comprehensive information on ground-water withdrawals for irrigation is essential in testing and incorporating the ground-water flow model as a tool for evaluation of management alternatives. A variety of reported information was available for development and testing of the ground-water flow model. However, rapid changes in cropping practices and irrigation techniques have occurred in recent years on the High Plains. Consequently, timely information on ground-water use for irrigation is needed to ensure that changing trends in water use are incorporated in the model. This report describes the analysis of Landsat-satellite data to derive acreage estimates of irrigated cropland. Irrigated-cropland acreage data were combined with sampled information on irrigation withdrawals to estimate ground-water use for irrigation on the High Plains.

The High Plains includes an area of about 174,000 mi^2 east of the Rocky Mountains in the southern part of the Great Plains. Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming are included in the High Plains as shown in figure 1. Ground water withdrawn from the aquifer is the principal source of water for this important agricultural area. The High Plains aquifer is the shallowest and most abundant source of ground water

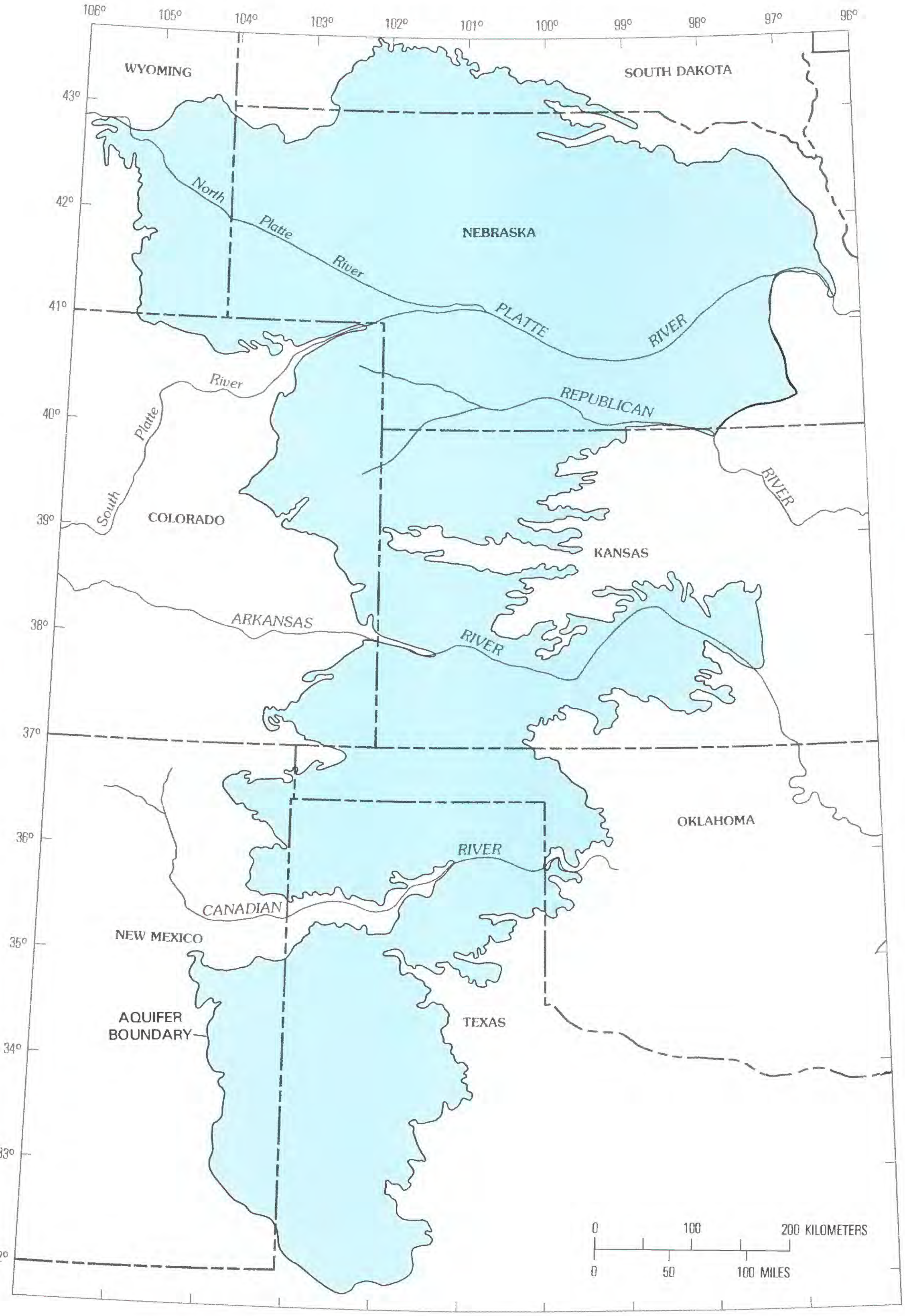

FIGURE 1.—Map showing location of High Plains aquifer.

in the region, and the agricultural economy of the High Plains is dependent on the aquifer for continued growth and prosperity.

PHYSIOGRAPHY AND CLIMATE

The High Plains is characterized by flat to gently rolling terrain that is a remnant of a vast plain formed by sediments deposited by streams flowing eastward from the Rocky Mountains. Erosion isolated the plains from the mountains and formed escarpments that typically mark the boundary of the High Plains.

Windblown sand and silt, derived from riverbeds, were deposited over large areas of the High Plains. The largest expanse of windblown sand deposits and dune topography in the Western Hemisphere (about 20,000 mi^2) is in north-central Nebraska. Within these sand hills, lakes and meadows occur between dunes where ground water is at or near land surface. Smaller areas of sand dunes occur in many parts of the High Plains.

Many lakes also occur on the High Plains outside of Nebraska. Most of these lakes are shallow depressions or playas that collect and store water only during runoff, although some of the deeper playas hold water throughout the year.

Generally, the High Plains has a typical middle-latitude, dry continental climate. The climate is one of abundant sunshine, moderate precipitation (less than 20 in./yr), persistent winds, little humidity, and rapid evaporation. Areas of the High Plains in central Kansas and eastern Nebraska that have average-annual precipitation greater than 20 in. typify the humid continental climate.

Mean annual precipitation ranges from less than 16 in. along the western edge of the High Plains to about 28 in. in eastern Nebraska and central Kansas (fig. 2). Mean annual precipitation increases eastward across the High Plains by about 1 in. every 25 mi. Typically, about 75 percent of the precipitation falls during the growing season, April through September, a condition favorable to agriculture. However, much of the precipitation results from local thunderstorms, so large variations in precipitation can occur from place to place.

Continental climates have large daily and seasonal extremes of temperature. The daily range of temperature may vary 15°–30°C. The seasonal extremes of temperature vary about 70°C between winter lows and summer highs.

The soils of the High Plains are ideally suited to agriculture. However, little precipitation and rapid evaporation in the region are limiting factors affecting production from nonirrigated crops. Persistent winds and high summer temperatures cause rapid rates of evaporation in the High Plains. Mean annual evaporation from Class-A pans varies from less than 60 in. in south-central South Dakota and northern Nebraska to more than 105 in. in west-central Texas and southeastern New Mexico (fig. 2). Because of the large evaporative demand, most of the water that enters the soil from precipitation is returned to the atmosphere by evapotranspiration. Recharge to the ground-water system may be several inches per year in sand-dune areas; but, throughout the much larger part of the High Plains where soils can hold the water for subsequent evapotranspiration, recharge averages a fraction of an inch per year (Gutentag and others, 1984).

AGRICULTURAL DEVELOPMENT

Nonirrigated agriculture and cattle grazing began on the High Plains during the late 1800's and flourished until the drought of the 1930's. The "dust bowl" years of the 1930's coupled with technological advancements in well drilling and pumping equipment and the availability of cheap energy spurred development and growth of irrigated agriculture in the region. Development of irrigation resulted in large increases in crop yields and removed many of the risks associated with nonirrigated agriculture.

Development of irrigation during the 1940's and 1950's was greatest in the southern High Plains, principally in Texas. Initial development was greatest in this area because of the availability of large quantities of inexpensive natural gas, shallow depths to the water table, and financial backing. During the years since the 1950's, irrigation development has spread throughout most of the High Plains.

The development of the center-pivot irrigation system enabled vast areas of land to be irrigated that previously were not suitable for irrigation because of topography. The rapid increase of irrigation in the High Plains is illustrated in figure 3.

Irrigation development has transformed the High Plains into one of the major agricultural areas in the United States. During 1977, about 35 percent of the area of the High Plains was cropland, and about one-half of that area was irrigated. Irrigated cropland on the High Plains currently represents more than 20 percent of the total irrigated land in the United States. Receipts for crops and related livestock production in the High Plains during 1977 were about 15 billion dollars (Grubb, 1978).

About 30 percent of the ground water used in the United States is pumped from the High Plains aquifer.

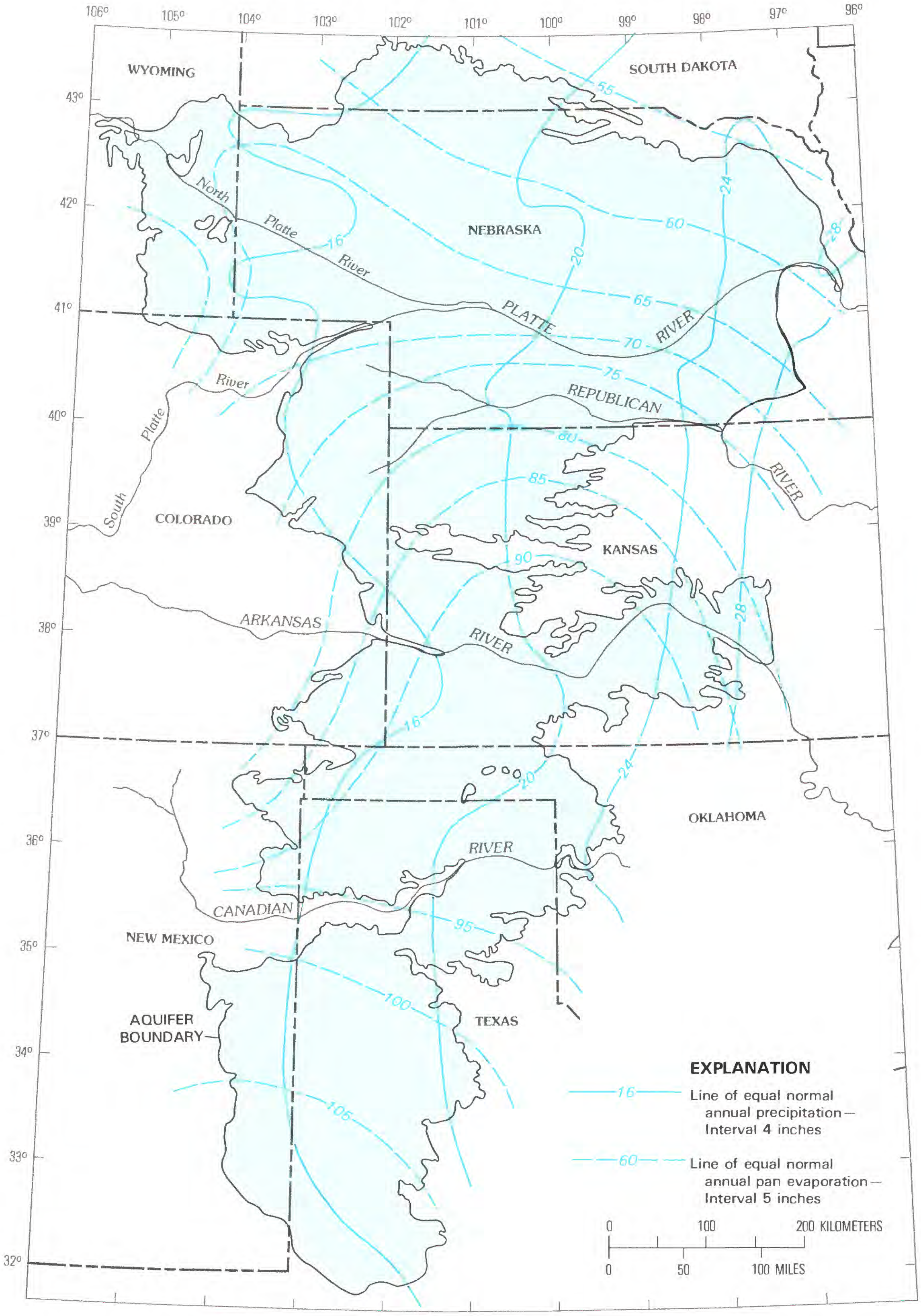

FIGURE 2.—Map showing normal annual precipitation and Class-A-pan evaporation in the High Plains.

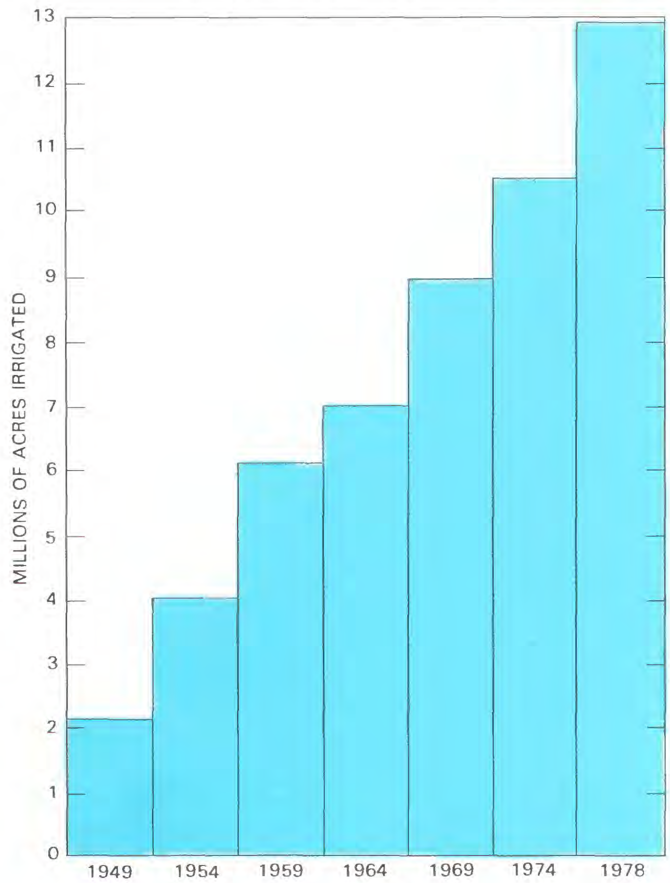

FIGURE 3.—Graph showing acreage irrigated by ground water in the High Plains from 1949 to 1978.

Ground-water withdrawal for irrigation has caused extensive water-level declines in some areas of the aquifer (fig. 4). These declines resulted in decreased well yields and increased pumping costs. The water-level declines, combined with increases in all costs associated with irrigation, especially energy, have caused a great deal of concern about the viability of future irrigation on the High Plains. Reliable and timely information on the volume and areal distribution of water used for irrigation is essential to the effective management of the water in the High Plains aquifer.

APPROACH FOR MAPPING AND WATER-USE DETERMINATION

The approach of relating sampled irrigation withdrawals to irrigated acreage was developed because existing data about ground-water withdrawals for irrigation were insufficient for use with the ground-water flow model. Unlike depth-to-water measurements, no agency maintains a network of systematically inventoried ground-water withdrawals throughout the High Plains. It was not economically feasible to establish a network to directly measure withdrawals from all irrigation wells in the High Plains, and withdrawals measured from a sample of irrigation wells cannot be directly extrapolated to estimate withdrawals from wells that have not been measured. Consequently, an indirect method was developed that related randomly sampled data about ground-water withdrawals for irrigation to the acreage irrigated. The volume of water pumped at each of the randomly selected sample sites was related to the acreage and crop type irrigated at the site to compute an average depth of applied irrigation water per acre by crop type. Depths of applied irrigation water were then related to empirical estimates of the amount of irrigation water required (irrigation demand). This relationship was used to estimate depths of applied irrigation water for unsampled areas. Estimates of depth of applied irrigation water were subsequently combined with irrigated-acreage information to provide areal estimates of the volume of irrigation water applied.

Development of this approach for use in the High Plains was done during the 1979 growing season. The results from the 1979 work were then used to establish a combined sampling and irrigated-acreage mapping effort to provide estimates of ground-water withdrawals for irrigation throughout the entire High Plains for the 1980 growing season.

The developmental effort conducted in 1979 concentrated on establishing procedures and developing techniques and equipment for (1) sampling ground-water withdrawals at randomly selected sites in the High Plains and (2) defining a suitable approach for mapping irrigated cropland for the entire High Plains (174,000 mi^2). This report focuses on the development and application of the methods used for mapping irrigated cropland. Consequently, the details of the approach used and the data collected for determining the volume of ground water pumped at randomly selected sampling sites for 1979 are not discussed here. Detailed information on the developmental work conducted during 1979 is contained in Heimes and Luckey (1980). A complete discussion of the approach used and the sampled ground-water withdrawal data obtained for the High Plains during the 1980 growing season is contained in a second report by Heimes and Luckey (1983). A summary of the approach used and the results obtained for 1980 is contained in the "Water-Use Determination" section of this report.

A number of approaches were tested for mapping irrigated cropland during 1979. An eight-county test area located in the northern High Plains was selected for testing various approaches and data sources for mapping irrigated cropland. The test area (fig. 5) included

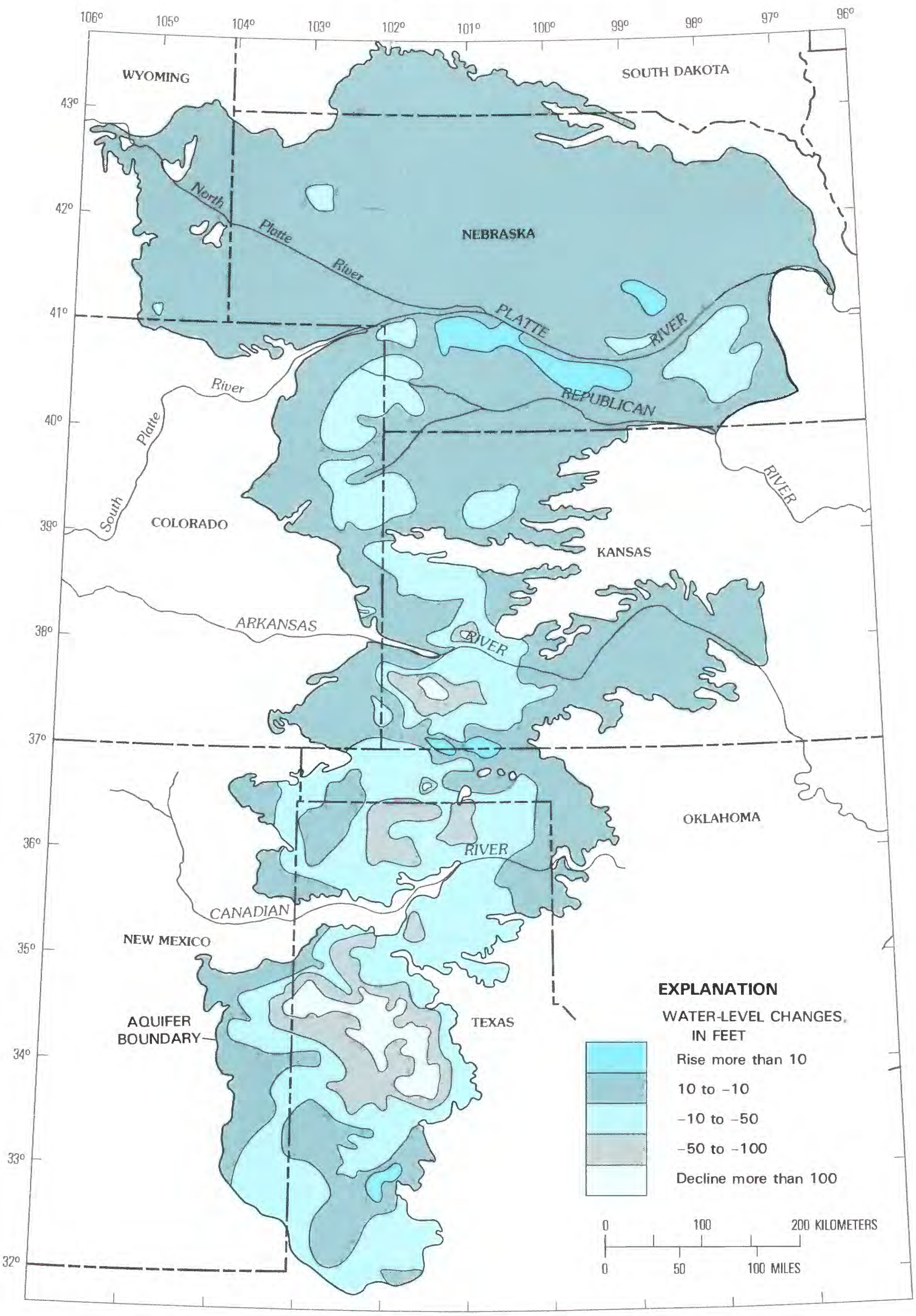

FIGURE 4.—Map showing predevelopment to 1980 water-level changes in the High Plains aquifer.

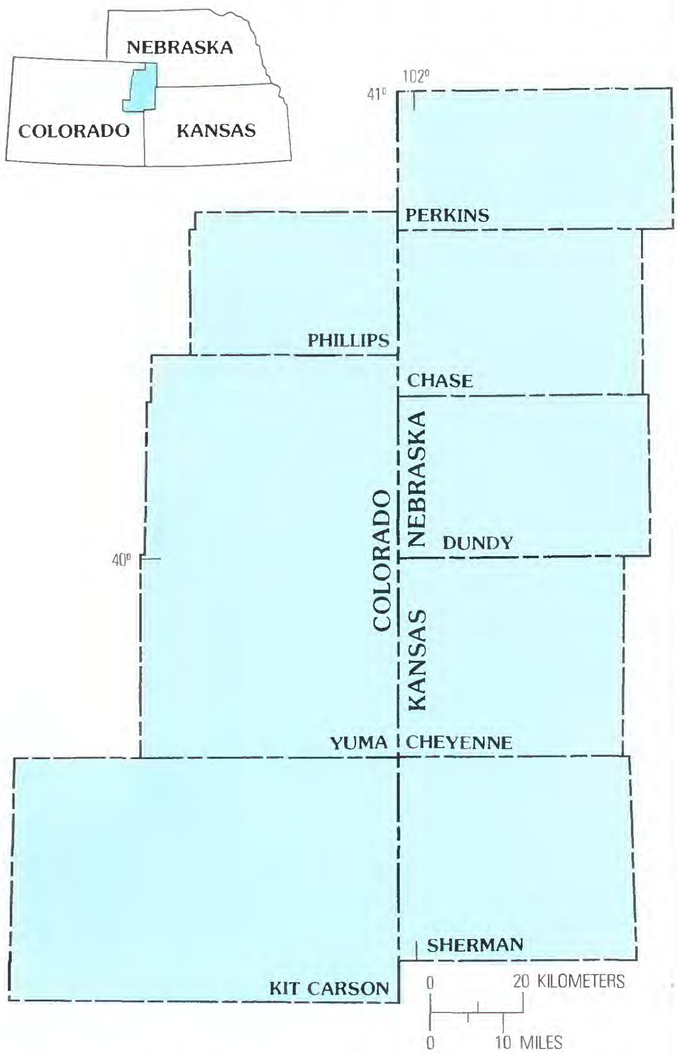

FIGURE 5.—Map showing location of eight-county test area in Colorado, Kansas, and Nebraska.

three counties (Phillips, Yuma, and Kit Carson) in Colorado, two counties (Cheyenne and Sherman) in Kansas, and three counties (Chase, Dundy, and Perkins) in Nebraska. Five approaches were tested to evaluate their suitability for mapping irrigated acreage over an area as large as the High Plains. The five approaches were: (1) compilation of maps using reported data from the U.S. Department of Agriculture, Agricultural Stabilization and Conservation Service (ASCS); (2) compilation of maps from physical inventories conducted in the field; (3) compilation of maps from 1:24,000-scale color-infrared aerial photographs; (4) compilation of maps from a combination of 1:80,000-scale color-infrared aerial photographs and Landsat-satellite images; and (5) compilation of maps from both visual and digital interpretations of Landsat multispectral-scanner (MSS) data.

A detailed discussion of each of the five approaches is contained in Heimes and Luckey (1980). All of the approaches tested were capable of providing maps of irrigated cropland with suitable detail and accuracy for use in estimating irrigation withdrawals throughout the High Plains. In fact, several of the approaches tested provided accuracies and detail much better than that required. However, detail and in some instances accuracy proved to be directly related to the effort and cost required to produce the maps. More detail resulted in greater costs and in more time and resources being required to produce maps of irrigated cropland (Heimes and Luckey, 1980). Of the five methods tested, only the approach using Landsat data was found to be suitable for application to an area as large as the High Plains. The other four methods were too costly and time consuming for application to such an extensive area. Conversely, the smaller scale, lesser cost, and repetitive coverage of the Landsat data made that approach ideally suited to mapping irrigated cropland throughout a large area. As a result of the evaluation of mapping techniques discussed above, Landsat data were selected as the principal source for mapping irrigated cropland on the High Plains.

The next three sections of this report discuss in detail the evolution of the Landsat mapping of the High Plains from the preliminary evaluation conducted in the eight-county test area to the completion of an integrated data set consisting of acreage and map information for irrigated cropland, nonirrigated cropland, and rangeland for the entire High Plains. Each of the three sections discusses discrete phases of the analysis of Landsat data.

The first phase was an initial evaluation of the suitability of Landsat for mapping irrigated cropland in the High Plains. This phase was conducted in Phillips and Yuma Counties, Colo., which were located in the eight-county test area. Both visual and digital interpretations of Landsat images were evaluated for suitability and accuracy in mapping irrigated cropland.

The second phase was a test to map the majority of the High Plains using 1978 Landsat data. This phase incorporated the results obtained in the test area to design the approach to be used. The 1978 test was conducted primarily to (1) develop the procedures necessary to analyze the large number of scenes required to cover the entire High Plains and subsequently merge data from individual scenes into an integrated data set of the entire area and (2) evaluate how environmental factors (changing climate and growing seasons) and cultural factors (different crops and irrigation practices) would affect the procedures used in analyzing the data and the results obtained for various locations in the High Plains.

The results of the phase-two effort, using 1978 Landsat data, were refined and used for the third phase, mapping of irrigated cropland for the entire High Plains for the 1980 growing season. Fifty-nine individual Landsat scenes were analyzed and interpreted to provide maps of irrigated cropland and tabulations of irrigated acreage on the High Plains during 1980.

Summaries of irrigated-cropland acreages, compiled from 1980 Landsat data, were used to develop estimates of irrigation-water use for use in the ground-water flow model of the High Plains aquifer. Nonirrigated cropland and rangeland acreage summaries, compiled from 1978 Landsat data, provided additional information which could be used to help allocate estimates of recharge. The procedures used to develop these estimates are discussed in the "Water-Use Determination" section, which follows the discussion of mapping irrigated cropland from Landsat data.

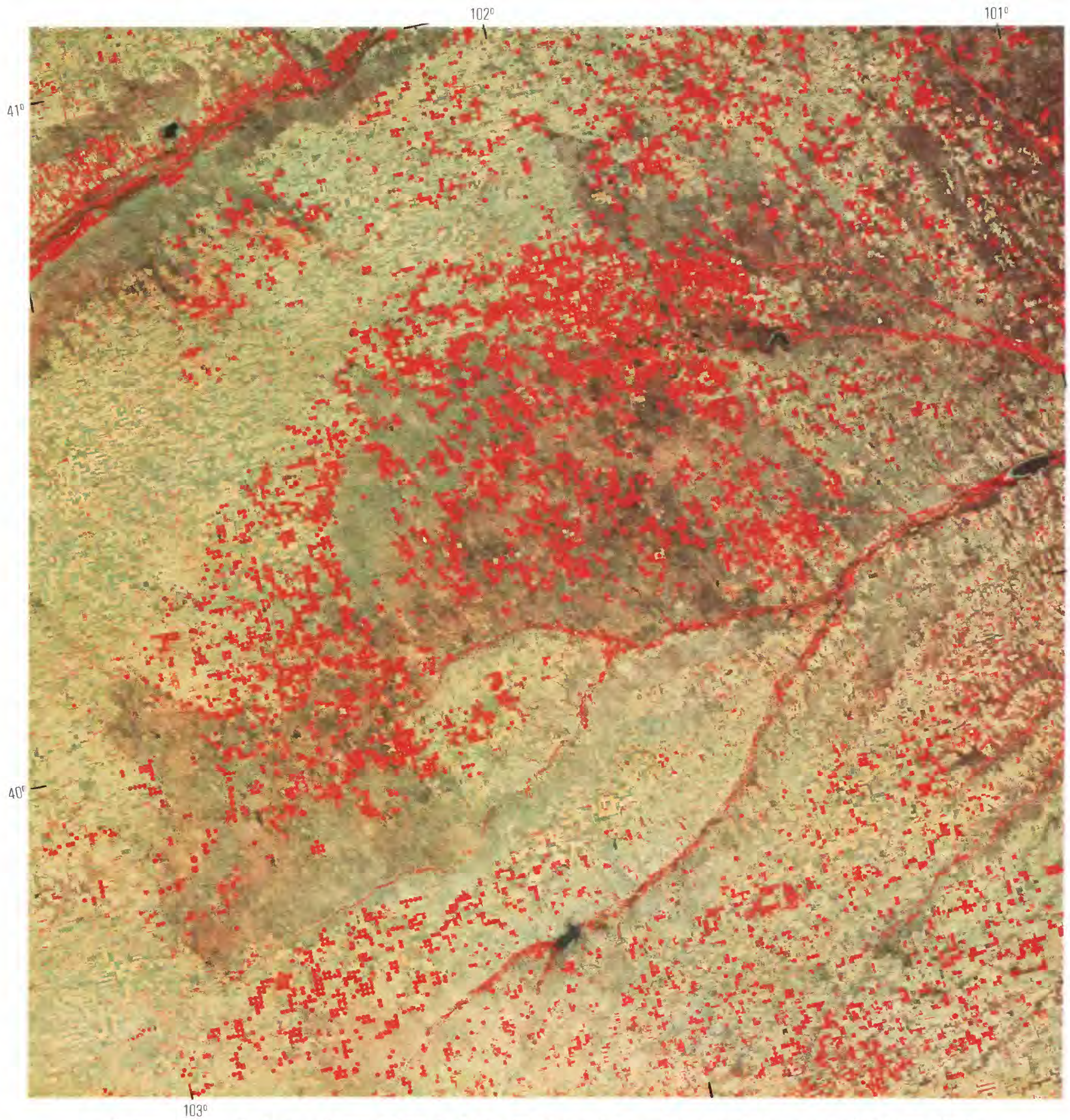

FIGURE 6.—Landsat scene 21282–16303, including Phillips and Yuma Counties, Colo., acquired July 27, 1978.

MAPPING FROM LANDSAT DATA

PRELIMINARY COUNTY TEST

A Landsat scene acquired July 27, 1978 (scene 21282–16303), was used for both visual and digital interpretation of irrigated cropland for Phillips and Yuma Counties, Colo. (fig. 6). A map of irrigated cropland for the same area and season also was compiled from high-resolution data (compiled from security-classified materials). The map compiled from high-resolution data was used to evaluate the accuracy of maps generated from the visual and digital interpretation of Landsat data. The high-resolution data were not considered a viable source for general mapping of the High Plains because of their limited availability.

Summarized results of the Landsat mapping are presented here; a detailed discussion of the analysis procedures and the results are reported by Thelin and others (1981). The Landsat data were analyzed using both visual and digital-analysis techniques because it was not known which of the techniques would be suitable to map irrigated cropland for an area as large and diverse as the High Plains. From the standpoint of efficiency of data processing for a large number of scenes, and providing the tabulations of irrigated acreage which were required for use with the High Plains data base, digital analysis is superior to visual-image interpretation. However, because of the diversity in climate, crop-types, and irrigation practices present in the High Plains, digital analysis, which relies solely on spectral-reflectance values to identify vegetation types, might provide less accuracy than a photo-interpretation (visual) technique that can incorporate spatial patterns along with the tones related to spectral reflectance.

Irrigated cropland was visually interpreted for Phillips and Yuma Counties in Colorado using a 1:250,000-scale Landsat color-composite image. Simple guidelines were established for visual interpretation. All fields on the Landsat image appearing bright red, indicating lush vegetation, were delimited as irrigated cropland. Other areas appearing bright red but not having obvious field patterns, such as riparian vegetation, were excluded. Using a color-composite image and base map at 1:250,000 scale, all fields meeting these criteria were delimited as polygons on a dimensionally stable base map. The three major types of irrigated cropland that were identified for Phillips County—center-pivot fields actively irrigated, non-center-pivot fields actively irrigated, and center-pivot fields not actively irrigated—are shown in figure 7.

Landsat digital data for July 27, 1978, were analyzed for an area of about 11,800 mi^2 including all of Phillips and Yuma Counties, Colo., and most of the remaining eight-county test site. National Aeronautics and Space Administration (NASA) Earth Resources Laboratory Applications Software (Junkin and others, 1980), installed on an in-house minicomputer, was used to define the spectral statistics for classifying the Landsat data into land-cover classes. Using an automated approach, a 6×6-pixel window was passed through the four bands of Landsat multispectral data and used to identify blocks within the data that were spectrally homogeneous. These blocks were used to define clusters that were then used to classify the full Landsat scene. The classification was displayed on a color monitor and visually interpreted to relate spectral statistics to land-cover categories. Spectral statistics having large values (reflectances) in the infrared bands and small values in the visible-red (chlorophyll absorption) band readily identified irrigated cropland. Other land-cover classes (rangeland and nonirrigated cropland) also had characteristic responses in the spectral bands that correlated with specific spectral statistics. The results of the digital analysis are presented as a color-coded map of Phillips County in figure 8, with each of the four land-cover classes (irrigated cropland, nonirrigated cropland-fallow, nonirrigated cropland-stubble, and rangeland) mapped as a separate color.

A map of Phillips County, depicting irrigated-cropland categories derived from high-resolution data, is shown in figure 9. The map was compiled using photo-interpretation techniques like those used in the visual analysis of Landsat data. Four categories of irrigated cropland are displayed: center-pivot actively irrigated cropland, non-center-pivot actively irrigated cropland, center-pivot not actively irrigated cropland, and non-center-pivot not actively irrigated cropland.

Results from Landsat visual and digital interpretations, and from the interpretation of high-resolution data are presented in table 1. The table compares the irrigated acreage, mapped by each of the three methods, for Phillips and Yuma Counties, Colo. All three methods produced similar acreage estimates. The largest percent difference occurred between the Landsat visual interpretation and the interpretation of high-resolution data.

Differences between the maps compiled from visual interpretation of Landsat imagery and high-resolution data were compared to data available at ASCS offices in Phillips and Yuma Counties. ASCS data showed that most of the differences were the result of nonirrigated corn, sorghum, and millet being identified as irrigated on the map compiled from the Landsat image. Examination of the Landsat image indicated that this problem generally could be avoided by altering the visual criterion for the intensity of infrared response that was equated with irrigated cropland. Differences between

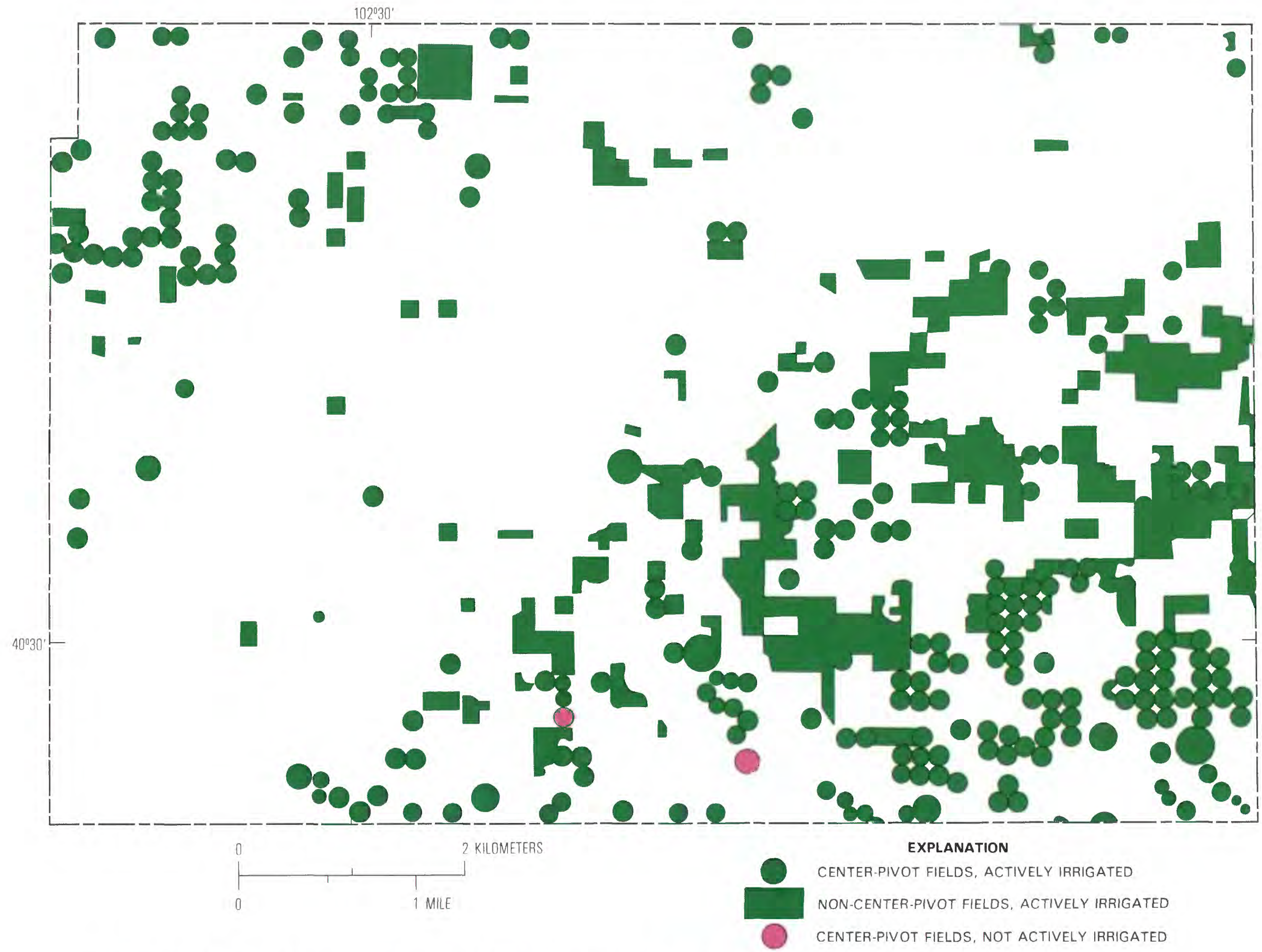

FIGURE 7.—Map showing visual interpretation of irrigated cropland for Phillips County, Colo., mapped from a Landsat color-infrared image.

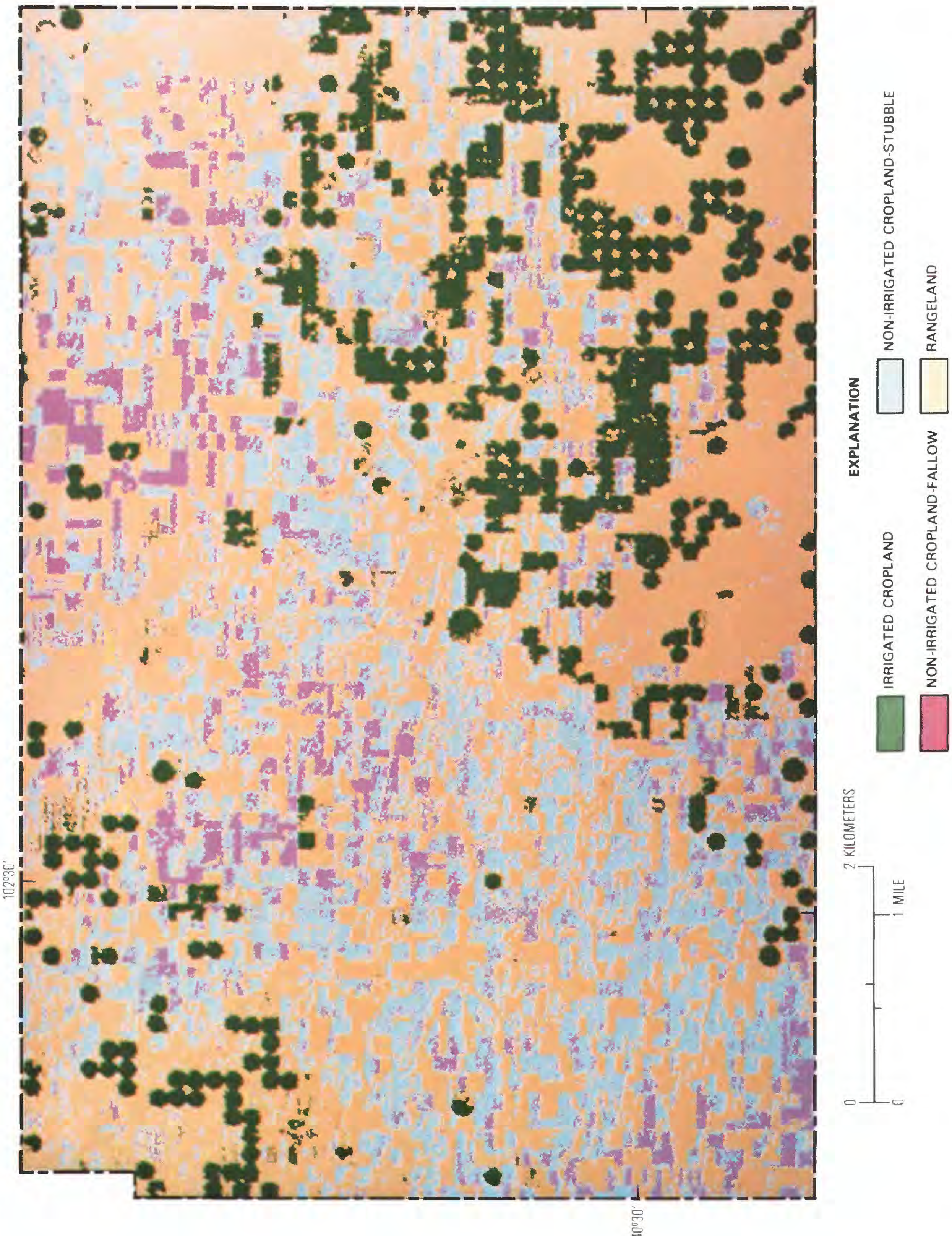

FIGURE 8.—Map showing digital classification of irrigated cropland, nonirrigated cropland-fallow, nonirrigated cropland-stubble and rangeland for Phillips County, Colo., mapped from Landsat data.

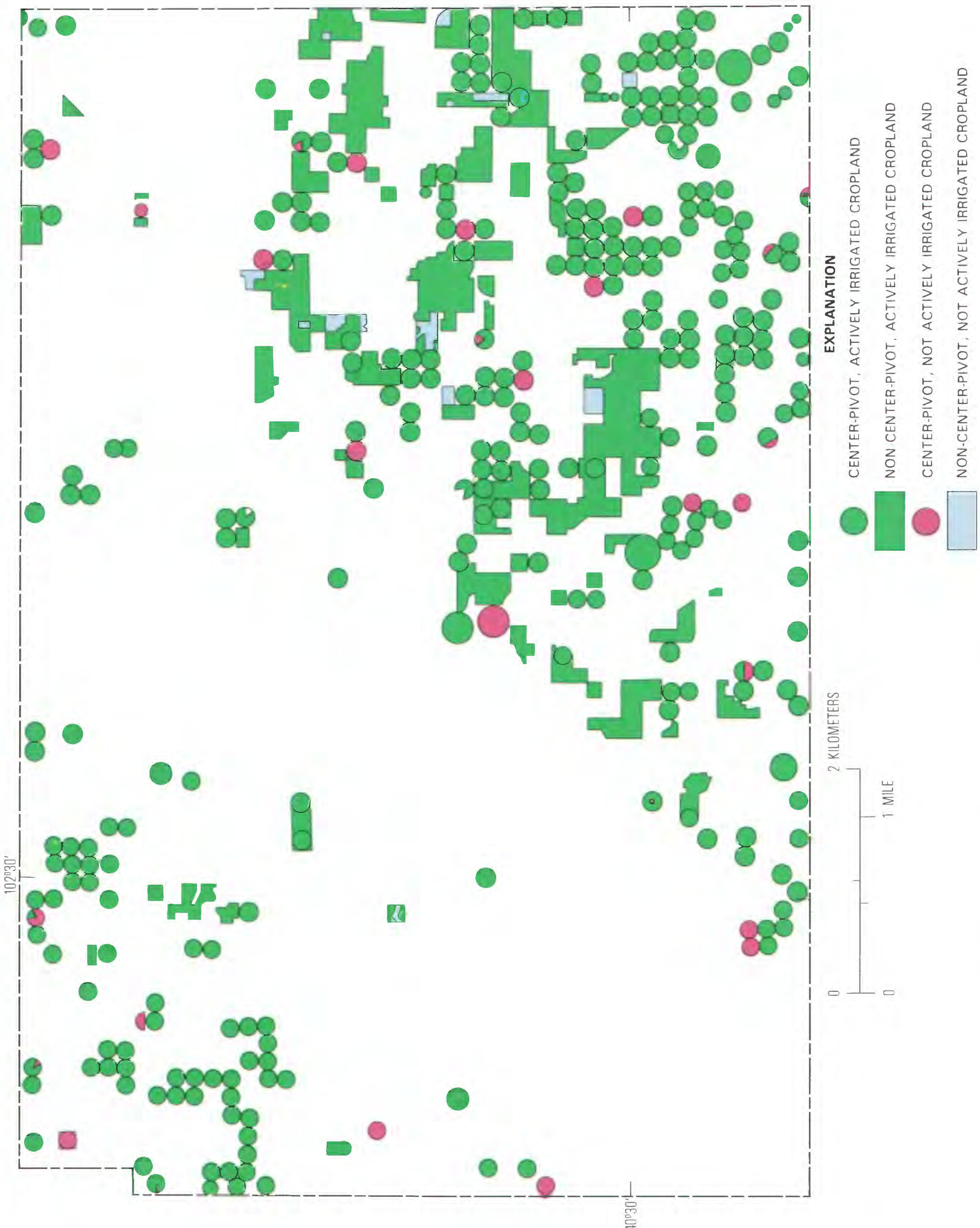

FIGURE 9.—Map showing irrigated cropland for Phillips County, Colo., mapped from high-resolution data.

TABLE 1.—*Irrigated-cropland estimates for Phillips and Yuma Counties, Colo., 1978*

Data source	Irrigated cropland (acres)		
	Phillips County	Yuma County	Total
Interpretation of high-resolution data	66,037	243,506	329,543
Landsat visual interpretation	69,152	235,836	304,988
Landsat digital interpretation	65,031	244,418	309,449

these nonirrigated cropland areas could be seen as changes in tone on the Landsat color-composite image.

Differences between the maps compiled by digital analysis of Landsat data and high-resolution data also were compared to data available at ASCS offices in Phillips and Yuma Counties. Only three identifiable fields in Yuma County were classified differently on the two maps. ASCS records showed that the map made from high-resolution data correctly identified two wheat fields as irrigated, and the map made from the Landsat digital classification incorrectly identified the two fields as nonirrigated. Wheat had already been harvested on the date of the Landsat image (July 27, 1978), so the Landsat data for those fields did not have a spectral response representative of irrigated cropland. The third field, growing milo, was correctly identified as nonirrigated on the map made from high-resolution data and incorrectly identified on the Landsat map.

The results obtained in Phillips and Yuma Counties demonstrated that either visual- or digital-interpretation techniques of Landsat data could be used to estimate acreages of irrigated cropland with acceptable accuracy. However, because of the efficiency obtained in processing large volumes of data and providing numerical summaries for entry into the High Plains data base, Landsat digital data were selected for the second-phase mapping of irrigated cropland using 1978 Landsat data.

During the second phase, the digital-analysis techniques were extended to diverse areas of the High Plains. Procedures were developed to select optimal Landsat coverage, efficiently handle and process both single and multitemporal data, and summarize the classified Landsat pixel data into a form compatible with the High Plains data base.

1978 TEST

PROCEDURE

For efficient processing, a variety of computers, ranging from minicomputers to mainframe computers, were used in the analysis of 1978 Landsat data. Data for each Landsat scene were processed following six basic steps:

1. Data selection.—Landsat scenes were selected based on crop-phenology information and available cloud-free scenes.
2. Data preparation.—Landsat scenes were corrected to remove the skew present in the data, and to reference Landsat line-and-column coordinates to map latitude and longitude.
3. Multitemporal registration.—Landsat multitemporal scenes were generated by registering one date with an additional date and then merging two channels of data from each of the original scenes to form a new four-channel multitemporal scene.
4. Analysis.—Unsupervised clustering was used to classify the Landsat MSS data; each input pixel was assigned to one of the clusters following a maximum-likelihood decision rule.
5. Interpretation.—Each classification was interactively interpreted to assign each cluster to a land-cover category.
6. Aggregation.—Interpreted pixels for each Landsat scene were aggregated into 1-minute cells.

DATA SELECTION

To aid in the selection of Landsat coverage, information obtained from the 1974 Census of Agriculture (U.S. Department of Commerce 1949–78) was used to compile county maps showing the density and distribution of irrigated cropland by crop type for the High Plains. In addition, a generalized crop phenology was constructed for each of the major irrigated crops using information on planting and harvesting dates obtained from State offices of the U.S. Department of Agriculture, Statistical Reporting Service. This information, along with precipitation data, was used to select optimal dates of Landsat coverage to distinguish irrigated cropland from nonirrigated cropland and rangeland.

The survey of crop types from the Census of Agriculture identified six major irrigated crops distributed throughout the High Plains: corn, sorghum, winter wheat, alfalfa, soy beans, and cotton. Crop phenologies indicated that the majority of these crops could be differentiated from surrounding vegetation using a single Landsat scene acquired in late July or early August. At this time, the majority of irrigated crops have attained a full vegetative canopy and are being irrigated, while most of the nonirrigated crops have a less dense vegetative canopy and may be showing signs of water stress. However, two major crops, cotton and winter wheat, could not be mapped using a single midsummer scene. Winter wheat required a late-spring scene, and cotton required a late-summer scene in addition to the midsummer scene.

The purpose of the 1978 test was to develop and evaluate digital-analysis procedures for the diverse environments of the High Plains. Therefore, the test did not attempt to provide a complete map of irrigated cropland for the entire High Plains. Those scenes containing only a small part of the High Plains and limited areas of irrigated cropland (as determined from black-and-white, Landsat Band 5 images) were not analyzed. Additionally, to simplify the analyses and reduce the volume of multitemporal data used, no attempt was made to map irrigated spring crops. Instead, multitemporal analysis techniques were evaluated by analyzing only the midsummer and late-summer scenes required to map irrigated cotton. Despite these exclusions, diverse regions of the High Plains were analyzed, constituting a valid test of the procedures being developed.

A search of available Landsat scenes was made through the EROS Data Center, Sioux Falls, S. Dak., for June through September, 1978. Cloud cover was a critical factor in evaluating the suitability of Landsat data. Any scene with more than 10 percent cloud cover was excluded from consideration. Remaining scenes were selected based on cropping patterns, crop-phenology information, and precipitation data. A total of 35 Landsat scenes were selected for the 1978 test (table 2). These scenes provided single-date coverage for the majority of the High Plains and multitemporal coverage for a five-scene area in Texas.

TABLE 2.—*1978 Landsat scenes used for test mapping of irrigated cropland on the High Plains*

Path-row[1]	Scene identification	Date
31-33	21297-16142	August 11, 1978
31-34	21297-16145	August 11, 1978
31-35	30132-16350	July 15, 1978
32-31	21640-16322	July 20, 1979
32-32	21298-16195	August 12, 1978
32-33	21298-16201	August 12, 1978
32-34	21298-16204	August 12, 1978
32-35	21262-16191	July 07, 1978
32-36	30133-16411	July 16, 1978
32-36	21334-16231	September 17, 1978
32-37	30133-16413	July 16, 1978
32-37	21334-16234	September 17, 1978
32-38	30133-16420	July 16, 1978
32-38	21334-16240	September 17, 1978
33-30	30170-16445	August 22, 1978
33-31	21281-16241	July 26, 1978
33-32	21281-16244	July 26, 1978
33-33	21299-16260	August 13, 1978
33-34	21299-16262	August 13, 1978
33-35	21263-16250	July 08, 1978
33-36	30170-16472	August 22, 1978
33-36	21263-16252	July 08, 1978
33-37	21263-16255	July 08, 1978
33-37	30170-16475	August 22, 1978
34-31	21282-16300	July 27, 1978
34-32	21282-16303	July 27, 1978
34-33	21282-16305	July 27, 1978
34-34	21282-16312	July 27, 1978
34-35	30135-16521	July 18, 1978
34-36	21300-16330	August 14, 1978
35-30	30172-16562	August 24, 1978
35-31	21283-16355	July 28, 1978
36-30	21302-16421	August 16, 1978
36-31	30155-17022	August 07, 1978
37-30	30156-17074	August 08, 1978

[1]Path-row locations are shown in illustration on plate 1.

DATA PREPARATION

Some geometric distortion is inherent in Landsat data. To remove this distortion, two data-preparation steps were taken: (1) an initial geometric correction of the MSS data was used to remove the skew introduced while the satellite was scanning the rotating Earth, by establishing a correspondence between Landsat pixel coordinates and latitude and longitude, and (2) referencing was further refined by an additional step using more precise coordinate pairs.

The correction required to remove the skew present in the Landsat data is dependent on latitude, and was determined by digitizing a series of corresponding points from the Landsat image and 1:250,000-scale maps using EDITOR[1] software (Ray and others, 1975). A file containing the coordinate pairs was created for use in establishing geometric control. This was accomplished by computing a least-squares linear fit that determined the distance that successive rows and columns of Landsat data must be shifted to remove the skew and to align the data to approximate north. The accuracy of this initial calibration is limited by the precision with which points are digitized on both the map and the Landsat image. The parameters derived from this oblique-calibration file were submitted to a mainframe computer where data from each Landsat scene were corrected to approximate north.

A second and more precise calibration file was created to reference the skew-corrected Landsat data more accurately. For this precision calibration, 20 to 30 well-distributed control points were selected from each Landsat scene. Gray-scale maps generated from the Landsat data at about 1:24,000 scale were aligned with topographic maps of corresponding scale. Coordinate pairs were determined by digitizing the location of each control point from the map and ascertaining the corresponding line-and-column coordinates on the gray-scale printout. This series of coordinate pairs was then used to calculate a precision-calibration file containing

[1]EDITOR software is non-proprietary, public domain software.

second-degree polynomials that more precisely related skew-corrected Landsat row-and-column coordinates to latitude and longitude coordinates.

MULTITEMPORAL REGISTRATION

An additional preprocessing step was required for the five scenes in Texas having multitemporal coverage. Pixels from the late-summer scene (secondary scene) were positioned to correspond with those from the mid-summer scene (primary scene). Corresponding points from the primary and secondary scenes were digitized from 1:500,000-scale Landsat color-composite images. A least-squares analysis of these corresponding points was performed to obtain a linear transformation. This transformation was used to select, by computer, 340 corresponding point pairs from the primary and secondary scenes. Blocks of data surrounding each of the 340 point pairs were extracted from both the primary and secondary scenes. The size of the blocks differed for the primary and secondary scenes. Blocks from the primary scene were 64×64 pixels, and blocks from the secondary scene were 32×32 pixels.

Each pair of blocks was processed through a correlation algorithm. The algorithm shifted the position of the secondary block with respect to the primary block until the best fit was achieved. The best fit occurred when the pixels within the primary and secondary blocks were correlated with the maximum absolute value. These correlation values were analyzed using a third-degree polynomial. Those blocks with residuals greater than 0.5 of a pixel were deleted. A good correlation requires at least 60 well-distributed blocks after editing. The coefficients of the polynomials were used to generate a parameter file which served as a data base for the process of registering all pixels in the secondary scene to those in the primary scene. This parameter file was then forwarded to a mainframe computer where the pixels of the secondary scene were resampled to overlay those of the primary scene.

A final step was taken to decrease the volume of data that would be required for spectral analysis of the multitemporal data sets. Rather than using all four bands of data from both dates, two bands of data (band 5 and band 6) were extracted from each scene to form into a new four-band data set. Although this step decreased the volume of spectral information for the multitemporal scenes, spectral statistics were adequate to identify irrigated cropland for both dates.

ANALYSIS

The analysis procedure used in the 1978 test was modified from the approach used in the preliminary county test. Because of the volume of data being processed, use of the most efficient hardware and software available was necessary, as was unlimited access to computing facilities. The preliminary county test used software installed on an in-house minicomputer. However, because this software had not been fully tested, it was decided to use well-tested EDITOR software to analyze the 35 scenes of 1978 Landsat data. EDITOR software offered a full range of image processing capabilities and had been used successfully in several past projects (Morrissey and Ennis, 1981; Gaydos and Newland, 1978). The mainframe computer on which EDITOR software was installed permitted interactive processing for some of the analysis phases. Moreover, an integral feature of EDITOR was the use of a unique and very powerful experimental computer, ILLIAC IV, developed by the Defense Advanced Research Projects Agency (Ray and others, 1975). The ILLIAC IV was used to perform the computationally intensive cluster analysis and classification of the Landsat data.

The 35 skew-corrected, Landsat multispectral-data tapes were sent to a computer facility for analysis. After skew correction and rotation to north, each Landsat scene that originally contained 7.6 million pixels now had 2,670 rows and 3,985 columns and contained 10.6 million pixels, 3 million of which were background data (data assigned a value of 255). Because examination of every pixel was not necessary to develop the spectral statistics for cluster analysis, two data-reduction steps were taken prior to analysis. First, disk files were created from tape using every other row and column of Landsat data. The disk file contained spectral values for 2.5 million pixels. The data were further compressed by a process that created a weighted-window file. This file contained a tally of the number of occurrences of each unique multispectral value. The weighting program permits a maximum of 67,000 different values. If the limit is reached, the program automatically begins deleting or omitting those spectral values that occur only once. In this analysis, the limit was rarely reached.

Histograms generated from the weighted-window file displayed the proportional distribution of spectral intensities in any one of the four Landsat bands. By examining histograms of each MSS band and the Landsat color-composite image, initial spectral classes or clusters were defined. Once the number of clusters was determined, clustering of the weighted-window file was accomplished using the ILLIAC IV.

The clustering program produced a file of spectral statistics containing the means, covariance matrices, and measurements of intercluster separability for each spectral class. From these spectral statistics, an ellipse plot was generated using EDITOR software (fig. 10).

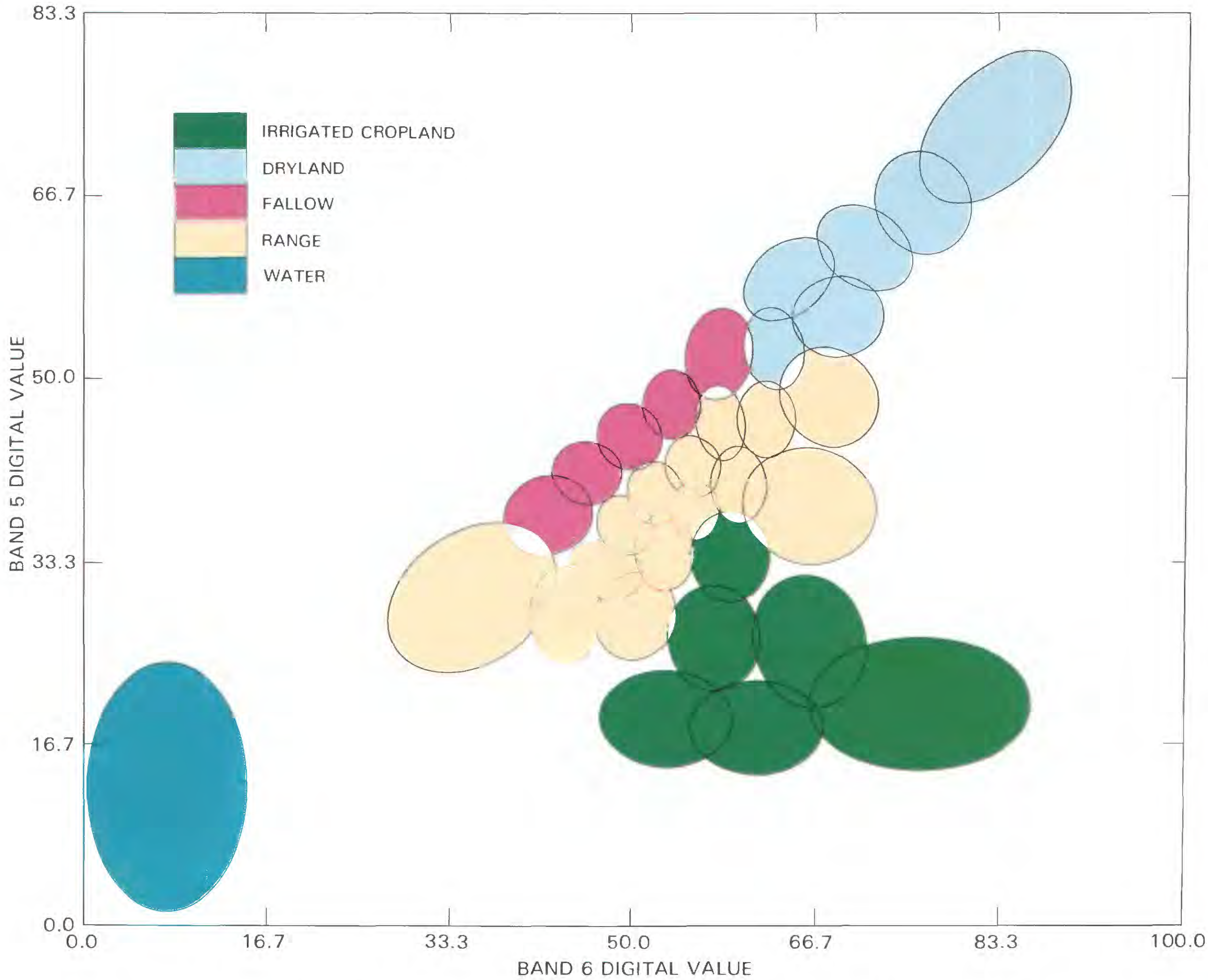

FIGURE 10.—Two-dimensional ellipse plot of clusters derived from clustering of Landsat-digital data.

The ellipse plot is a two-dimensional display of clusters in any two bands (an infrared and visible band, bands 5 and 6, were used), where the center of each ellipse represents the mean of the cluster, and the area covered by the ellipse represents the variance of the cluster. One method of determining if an adequate number of clusters had been defined during the clustering process was to analyze the ellipse plot. Typically, the analyst looked for signs that too few clusters had been defined as indicated by individual clusters with large variances (large-area ellipse) or minimal intercluster separabilities (overlap of ellipses). Statistics files were selected for classification if they contained clusters with small variances and adequate intercluster separabilities. If small-variance, readily separable clusters were not obtained, the weighted-window file was resubmitted to the computer for reclustering with a revised number of clusters. After completion of the reclustering process, statistics were again reviewed. Once the statistics file met the criteria of small variance and intercluster separability, it was ready for use in the classification of the Landsat data.

Most statistics files used to classify a Landsat scene contained between 32 and 45 clusters defined by the spectral statistics. However, the number of clusters varied with the spectral and environmental complexity of the area being classified. For example, some scenes in Nebraska were classified using a greater-than-average number of clusters to help avoid misclassification of rangeland as irrigated cropland. In more arid areas, fewer clusters were needed because a good contrast exists between irrigated cropland and the surrounding vegetation.

The High Plains boundary and county boundaries were digitized from 1:500,000-scale State maps for each Landsat scene prior to classification of the pixel data. Mask files, defining areas within the High Plains boundary, were created by referencing the digitized boundary data to latitude and longitude coordinates obtained from the precision-calibration file. The mask file and spectral statistics were transferred to the ILLIAC IV and used to classify the Landsat data within the boundary. Using the Gaussian maximum-likelihood classification algorithm (Swain, 1972), discriminant functions for every pixel for each spectral class were calculated based on means and covariance matrices. Each pixel was then assigned to the spectral class for which the discriminant was at a maximum.

The masked-classification procedure resulted in an overlay of the classified pixels with the digitized aquifer and county boundaries. This approach allowed the aggregation of irrigated, nonirrigated, and rangeland acreage for counties or parts of counties within the High Plains boundary.

INTERPRETATION

One advantage of the unsupervised clustering procedure was the creation of spectral classes for a variety of land-cover categories. Although the primary emphasis was to identify irrigated cropland, other land-cover categories were indentified that could provide additional information. For example, information on the areal distribution of nonirrigated cropland and rangeland acreage could be useful for estimating recharge to the aquifer. The eight land-cover categories identified were irrigated cropland, nonirrigated cropland, rangeland, riparian or swale vegetation, forest land, water, barren land, and playas. Categories for clouds and shadows also were identified.

During the interpretation, each classified Landsat scene was viewed on a color display. Spectral classes were assigned to land-cover categories by assigning a distinctive color to each spectral class and then comparing the color coded display of the classification with topographic maps, color-composite Landsat images, cluster plots, and available ground data. Later, all spectral classes representing a particular land-cover category were assigned one color and compared to other classes and supplementary data to refine the land-cover classification.

AGGREGATION

Software developed on a minicomputer was used to aggregate interpreted data into 1-minute cells for use with the High Plains data base. To perform this aggregation, it was necessary to assign latitude and longitude coordinates to each of the nearly 10 million pixels of a Landsat scene using the precision-calibration file. An algorithm was developed that assumed the image transformation for a given row of pixel coordinates to be convex. Following this assumption, a piecewise-linear approximation was calculated which resulted in fewer computations for each line of data. This allowed the computation of the image transformation at a lesser cost with no substantial loss of accuracy. Data for each of the 35 Landsat scenes were aggregated on a minicomputer, requiring about 1 hour per scene.

Precision-calibration files for each of the classified Landsat scenes were used to determine the number of irrigated pixels in each 1-minute cell. The total number of irrigated pixels contained in a 1-minute cell were then divided by the total pixels in the cell to derive the percentage of the cell that was irrigated. The same procedure was used to calculate the percentage of nonirrigated cropland and rangeland. When all of the scenes were aggregated, three separate files of data were available containing the percentage of each of the approximately 174,000 1-minute cells mapped as irrigated cropland, nonirrigated cropland, or rangeland. If a single cell was covered by two overlapping Landsat scenes, data from the two scenes were averaged. For each 1-minute cell, the percentage of irrigated cropland, nonirrigated cropland, and rangeland was computed and stored in three separate files for use with the High Plains RASA data base.

MAP PRODUCTS

Three digitally mosaicked maps of the High Plains displaying the density (percentage) of irrigated cropland, nonirrigated cropland, and rangeland are shown in figure 11. These maps were produced using the 1-minute cell data. Although density calculations were made to the nearest percent for each 1-minute cell, assigning them to broad intervals for map presentation caused some abrupt lines to appear because adjacent cells that differed by just a few percent, but were allocated to different intervals, were colored differently.

After completion of the classification and interpretation of the 35 individual Landsat scenes, a final pictorial presentation of the data was prepared. Each digital Landsat-classification tape was displayed using a film recorder, and each of the interpreted land-cover classes was assigned a unique color. Color-film negatives were made for each Landsat scene and then printed. The color prints were manually mosaicked into one picture showing the distribution of the eight land-cover classes and categories representing clouds, shadows, and areas not classified (fig. 12).

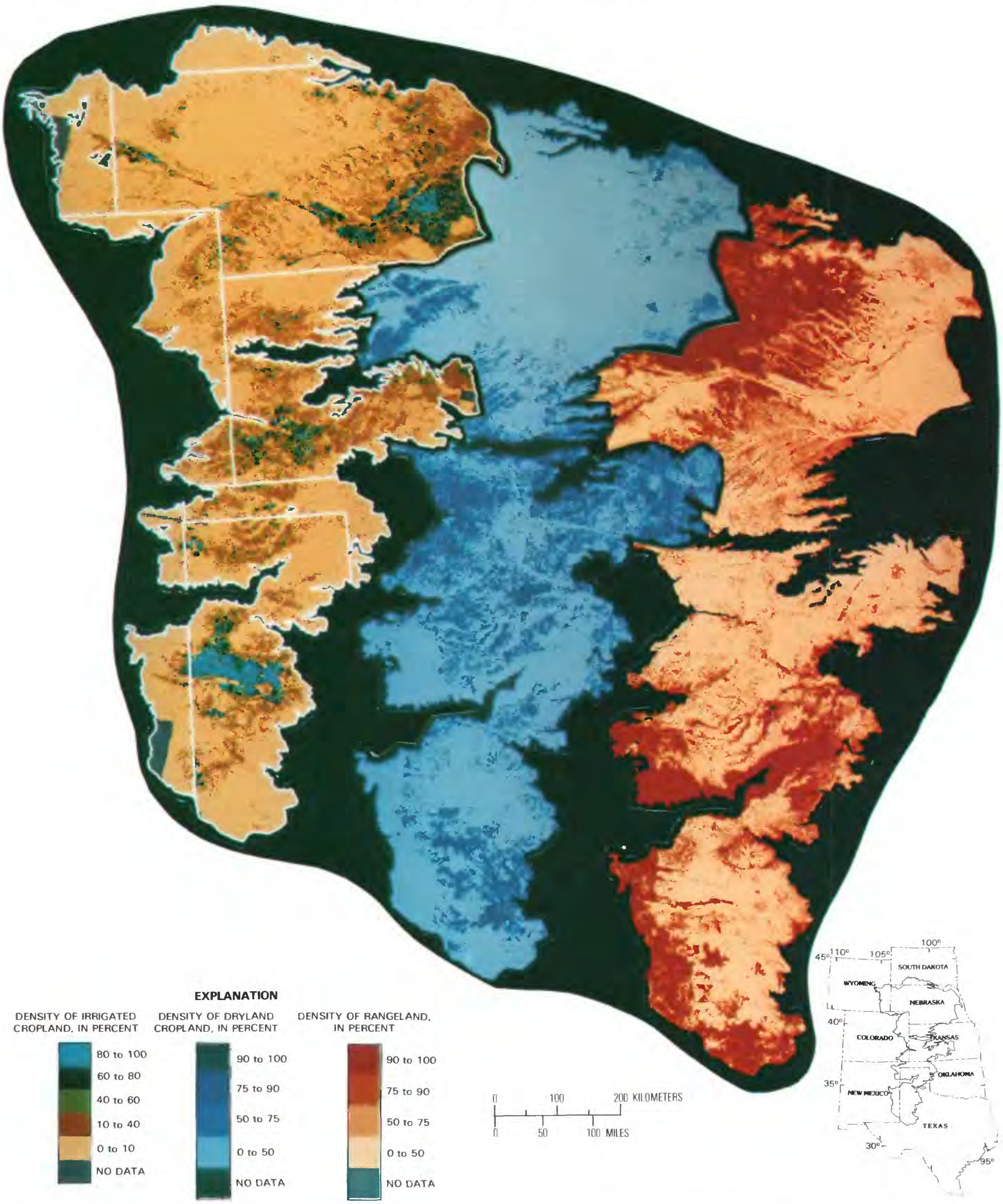

FIGURE 11.—Digital mosaics of Landsat scene classifications of irrigated cropland, nonirrigated cropland, and rangeland in the High Plains.

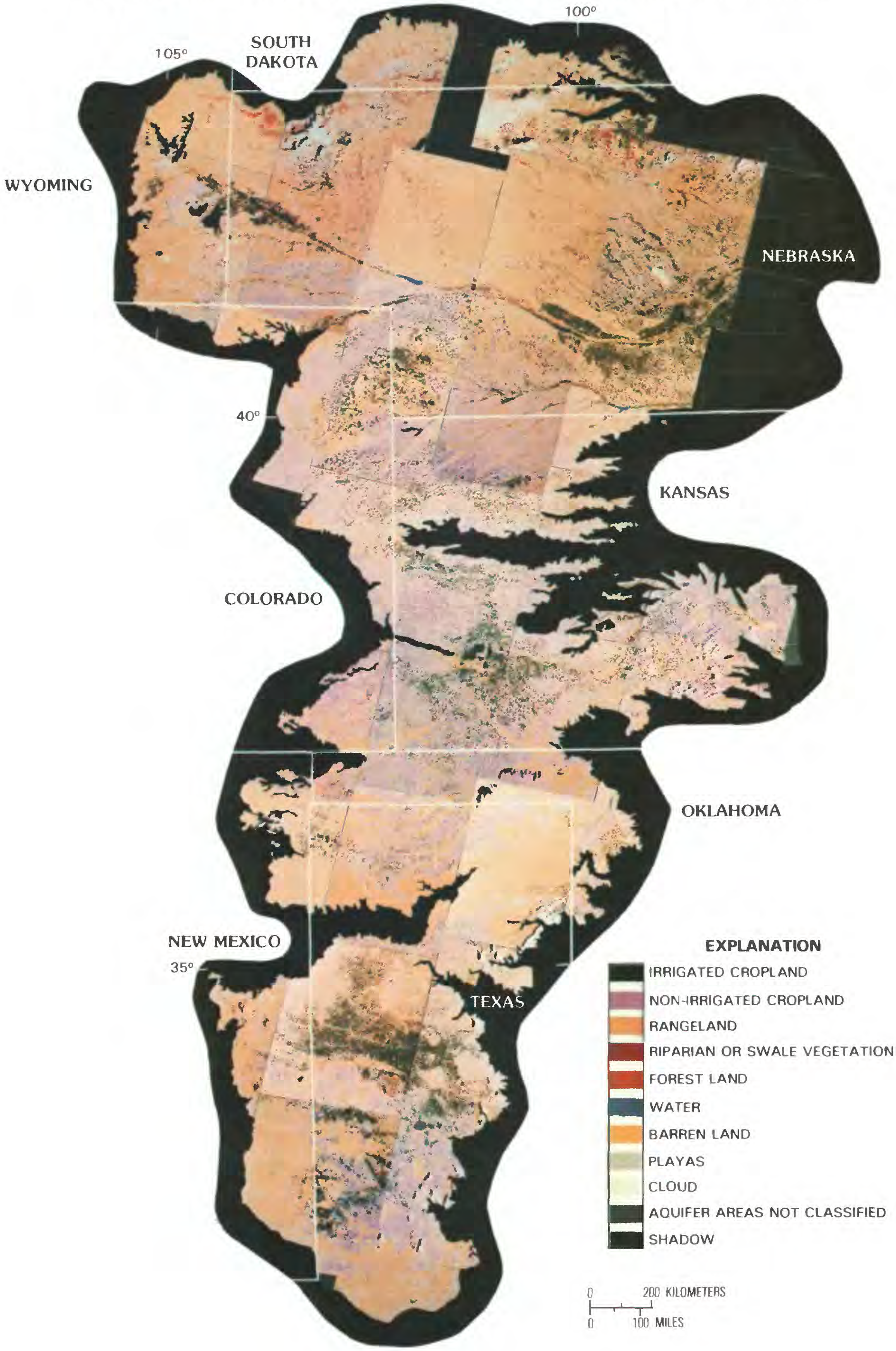

FIGURE 12.—Photomosaic of Landsat classifications for the High Plains showing eight land-cover classes.

CONCLUSIONS AND RECOMMENDATIONS FOR 1980 MAPPING

The 1978 test proved the utility of Landsat-digital data for mapping irrigated cropland for the areas tested in the High Plains. During this phase of the project, procedures were developed to process and analyze a large number of Landsat scenes. However, modifying many of these procedures was necessary to meet the goals for mapping irrigated cropland using 1980 Landsat data.

The procedure for selecting the Landsat data was refined. During the 1978 test, spring grains, a major irrigated crop throughout most of the High Plains, were not mapped. Detailed information on regional cropping practices was essential to ensure that all irrigated cropland would be mapped for 1980. Specifically, information was needed on planting and harvesting dates and growth stages when irrigated crops could best be distinguished from nonirrigated crops. To satisfy this requirement, a study was initiated with the Kansas Applied Remote Sensing (KARS) program. Information obtained from this study was used to construct a list of optimal spring and summer dates for distinguishing irrigated from nonirrigated crops (Martinko and others, 1981; Martinko and Kipp, 1982).

Modification of digital-analysis procedures was also necessary. Although clustering and classification of the Landsat digital data were successfully used during the 1978 test, these techniques were abandoned during the analysis of 1980 data. By 1980, Landsat data had undergone a change in formats. Data were being processed on the EROS Data Center's Digital Image Processing System (EDIPS). During EDIPS processing, a number of corrections are applied to the data, one of which is a resampling using cubic convolution. This correction produces data with a smoother appearance, but generates a greater range of spectral values. In attempting to create a weighted-window file to compress the EDIPS data, the program limit of 67,000 unique spectral values was quickly reached. Without the use of this data-compression technique, clustering entire Landsat scenes was impractical.

An alternative analysis technique was considered. The Irrigated Lands for Water Management Technique Testing project had reported success in inventorying irrigated cropland, within selected California test sites, using a band-ratio classification (Colwell and others, 1981). Calculation of band ratios is a simplified approach to data analysis that is performed by dividing the spectral value of each pixel in one band by the spectral value for that same pixel in another band. Dividing an infrared band (7) by the red band (5) creates a new image where the greater spectral values generally indicate lush (irrigated) vegetation. The band-ratio technique was an attractive alternative to cluster analysis because the software necessary to calculate band ratios could be easily implemented on a minicomputer.

Procedures for processing multitemporal scenes also needed revision. With 1978 data, values for two bands from each scene were used for cluster analysis. For the 1980 analysis, band ratios for multitemporal scenes were calculated independently. Following calculation of ratios, the secondary scene was registered to the primary scene and merged into one data set using a separate procedure.

Procedures for interpreting the classification of irrigated cropland were also improved. During the 1978 test, knowledge of the area obtained from ground data or photo interpretation could not be incorporated into the final classification. For example, riparian vegetation commonly was misclassified as irrigated cropland. To remedy this problem, Classified Image Editor (CIE) software (Hofman and others, 1983) was developed and implemented on a minicomputer. The development of the CIE software provided an interactive editing capability, making it easy to routinely edit out misclassifications and produce a more accurate inventory of irrigated cropland for 1980.

1980 MAPPING

PROCEDURE

The following six steps were used to analyze Landsat digital data and map irrigated cropland for the 1980 growing season:

1. Data selection.—Crop-phenology data were used to identify optimum dates for selecting Landsat scenes.
2. Analysis.—A ratio of band 7 to band 5 was used to classify irrigated cropland for each Landsat scene.
3. Interpretation.—The CIE was used to interpret and edit classifications of band ratios.
4. Data preparation.—Precision-calibration files were created for referencing Landsat pixel coordinates to map latitude and longitude.
5. Multitemporal registration.—Scenes were registered after interpretation of the ratio-classified Landsat data (step 3).
6. Reinterpretation and aggregation.—The ratio-classified data were reinterpreted to correct for errors in the initial interpretation and then were aggregated into 1-minute cells as percentages.

DATA SELECTION

To ensure that all irrigated cropland within the High Plains would be included in the 1980 inventory, a study was initiated with the KARS program. The objective of the study was to identify the optimal dates of Landsat coverage that would provide maximum distinction between irrigated and nonirrigated cropland. Recommendations for optimal Landsat scenes were based on crop phenologies, irrigation management practices, and distribution and density of the major crops (Martinko and others, 1981). Thirteen crops were identified as having significant acreage and were widespread enough to be included in the study. For each of these crops, two periods of time were identified (best and optional date) for distinguishing irrigated from nonirrigated cropland.

Using these recommendations as a guide, a list of available Landsat scenes was evaluated. Because of excessive cloud cover during the 1980 growing season, many recommended dates were unavailable. At this point, advantage was taken of the information contained in the KARS study. Phenological characteristics of major crops were used to further evaluate the suitability of Landsat data and select the best of the available scenes. A total of 59 Landsat scenes (table 3) were acquired that included multitemporal coverage for 18 of the scenes. Following recommendations outlined in the KARS study, a Landsat scene from a spring date was used in conjunction with a midsummer date for areas where winter grains constituted at least 10 percent of the total irrigated cropland. For the cotton-growing areas, the midsummer scene was supplemented with a scene from late summer. An area in Texas included both irrigated spring grains and cotton. For this area, a total of three dates of Landsat coverage were used to map irrigated cropland.

ANALYSIS

A table-look-up classifier program was designed to read the Landsat multi-spectral data, compute ratios, screen for data aberrations, and produce a ratio-classified scene. After EDIPS processing, each of 59 Landsat scenes was read into a minicomputer containing the classifier. The classifier used a table that contained ratio values for all possible combinations of Landsat bands 7 and 5. Instead of computing the ratios for each scene, the program simply identified the two input values from band 7 and band 5, and then searched through the table for these values and the corresponding ratio. The ratio was then multiplied by 1.5, a scaling factor that resulted in classified pixels in the range from 0 to 255. Also, the expected range of ratio values (band 7 and band 5) for clouds, shadows, and bad data were built into the table. Where these combinations of values occurred, the pixels were automatically assigned to special categories designated as cloud, shadow, or bad data.

TABLE 3.—*1980 Landsat scenes used for mapping of irrigated cropland on the High Plains*

Path-row[1]	Scene identification	Date	
30-33	22304-16254	May 14,	1981
30-33	21998-16270	July 12,	1980
31-30	30870-16233	July 22,	1980
31-31	30870-16235	July 22,	1980
31-32	30870-16242	July 22,	1980
31-33	22287-16313	April 27,	1981
31-33	30870-16244	July 22,	1980
31-34	21963-16322	June 02,	1980
31-34	30870-16251	July 22,	1980
31-35	30798-16280	May 12,	1980
31-35	30870-16253	July 22,	1980
32-30	30871-16291	July 23,	1980
32-31	22018-16380	August 01,	1980
32-32	22018-16382	August 01,	1980
32-33	30817-16323	May 30,	1980
32-33	22000-16383	July 14,	1980
32-34	30817-16325	May 30,	1980
32-34	22018-16391	August 01,	1980
32-35	30799-16334	May 12,	1980
32-35	22000-16392	July 14,	1980
32-36	30763-16350	April 06,	1980
32-36	22000-16395	July 14,	1980
32-36	22054-16402	September 06,	1980
32-37	22000-16401	July 14,	1980
32-37	22054-16405	September 06,	1980
32-38	22018-16405	August 01,	1980
33-30	30872-16345	July 24,	1980
33-31	30890-16342	August 11,	1980
33-32	22037-16442	August 20,	1980
33-33	22271-16431	April 11,	1980
33-33	22037-16445	August 20,	1980
33-34	30800-16390	May 13,	1980
33-34	22037-16451	August 20,	1980
33-35	30800-16393	May 13,	1980
33-35	22001-16451	July 15,	1980
33-36	30800-16395	May 13,	1980
33-36	22001-16453	July 15,	1980
33-36	30908-16355	August 29,	1980
33-37	30908-16361	August 29,	1980
34-30	22020-16490	August 03,	1980
34-31	22020-16493	August 03,	1980
34-32	22002-16494	July 16,	1980
34-33	22152-16414	April 23,	1979
34-33	22002-16500	July 16,	1980
34-34	30765-16453	April 08,	1980
34-34	22020-16504	August 03,	1980
34-35	30765-16460	April 08,	1980
34-35	22038-16512	August 21,	1980
34-36	30765-16462	April 08,	1980
34-36	22002-16512	July 16,	1980
34-36	22038-16514	August 21,	1980
35-30	22021-16545	August 04,	1980
35-31	22021-16551	August 04,	1980
35-32	22021-16554	August 04,	1980
35-33	30820-16494	June 02,	1980
35-33	22021-16560	August 04,	1980
36-30	22022-17003	August 05,	1980
36-31	30875-16522	July 27,	1980
36-32	30875-16524	July 27,	1980

[1]Path-row locations are shown in illustration on plate 1.

INTERPRETATION

Interpreting and editing the 59 Landsat ratio-classified scenes took the most time during the analysis procedure. The CIE software provided a fast and efficient tool for displaying and editing each of the scenes. Ratio-classified scenes having values ranging from 0 to 255 were displayed as gray levels on a color monitor. While viewing this gray-level representation of the classification, an analyst used the CIE cursor to determine the range of gray levels (0–255) that appeared to represent irrigated cropland. The range of gray levels identified as irrigated cropland was redisplayed in color, and a threshold was set that best represented the minimum gray level for irrigated cropland. Gray levels less than this threshold were interpreted and designated as nonirrigated land.

This threshold value did not always represent an absolute cutoff for irrigated cropland. On each classified scene, some areas that were not irrigated had the same ratio value as areas of irrigated cropland. The CIE cursor was used to outline these anomalous areas as polygons on the color monitor, and the range of gray levels was determined. A new threshold value was established within the polygon to separate the irrigated areas from nonirrigated areas.

The editing required for each Landsat scene varied with the environmental complexity of the area. Generally, summer scenes from the most arid parts of the High Plains required the least editing, whereas spring scenes required the most. For example, spring scenes with lush, herbaceous rangeland misclassified as irrigated cropland required extensive editing. Similarly, some spring and summer scenes required extensive editing to correctly map riparian vegetation (trees and shrubs occurring along drainages) as nonirrigated land.

DATA PREPARATION

Landsat data used for the 1980 mapping were in EDIPS format. As part of the EDIPS processing, the Landsat data are geometrically corrected to remove systematic distortion. Each EDIPS-processed, Landsat Computer-Compatible Tape (CCT) contained additional information that could be used to create a precision-calibration file for referencing the Landsat coordinates to a ground location. Precision-calibration files generated from this information were assumed to be accurate, eliminating the need to generate precision-calibration files manually.

Precision-calibration files for several Landsat scenes were generated using the EDIPS information. These files were used to calculate Landsat coordinates for an obvious map feature (lake or road intersection). These coordinates were used to retrieve the data and generate a gray-scale map of the area. The gray-scale map was overlaid on the corresponding 1:24,000-scale quadrangle map. Differences between the calculated and actual Landsat coordinates produced less than the required accuracy (±3 pixels). Consequently, the procedure using the EDIPS information had to be abandoned. Instead, the precision-calibration files were generated for each primary Landsat scene (see the discussion in the "Multitemporal Registration" section) by adopting the same manual approach used in the analysis of 1978 data.

MULTITEMPORAL REGISTRATION

After editing of the ratio-classified scenes, all scenes with multitemporal coverage were registered. A total of 18 scenes needed spring and summer coverage, of which 3 scenes in Texas required additional late-summer coverage. The registration process was virtually the same as that used in the analysis of 1978 data. One date of coverage was designated as a primary scene to which subsequent dates of coverage were registered. After this registration, a series of corresponding points were identified and digitized from Landsat color-composite images for both dates. These points were used to retrieve blocks of data from both the primary and secondary scenes. The processing of these blocks, through a series of steps, generated parameters necessary to transform the location of pixels from the secondary scene to the same location on the primary scene. Parameter files were created for each of the 18 scenes and used to register each set of ratio classifications.

After each ratio-classified scene was edited and the multitemporal data sets were registered, the data were reexamined to resolve any remaining classification problems. First, classes were reorganized into a format required for aggregation of the data. Second, areas classified as bad data (line-start problems with the Landsat 3 data, background, clouds, and shadows) were all converted to one class for special processing.

Multitemporal data were combined into one data set on the minicomputer after each of the scenes was edited and registered. The resulting multitemporal data set contained classes describing the pattern of irrigated cropland over time. Specific categories were created to designate all possible combinations of the three basic classes: irrigated cropland, nonirrigated land, and bad data. The nine possible classes resulting from a multitemporal image derived by combining spring and summer Landsat data are shown in figure 13. Any number of scenes could be merged, but the software only allowed for two scenes to be retained separately. In those cases where scenes from three separate dates were required,

CLASSES DERIVED FROM SUMMER LANDSAT DATA	CLASSES DERIVED FROM SPRING LANDSAT DATA: IRRIGATED CROPLAND	NON-IRRIGATED LAND	BAD DATA
IRRIGATED CROPLAND	Areas irrigated in both spring and summer	Areas irrigated summer only	Areas irrigated in summer. No information for spring date
NON-IRRIGATED LAND	Areas irrigated spring only	Areas not irrigated on either date	Areas not irrigated in the summer. No information for spring date
BAD DATA	Areas irrigated in spring. No information for summer date	Areas not irrigated in spring. No information for summer date	No information for either spring or summer dates

FIGURE 13.—Matrix of possible classes, derived from analysis of Landsat data.

two scenes were merged to produce a data set that was then treated as a single scene. This new single scene was then merged with the third scene.

REINTERPRETATION AND AGGREGATION

The final phase of analysis consisted of aggregating data from the 59 ratio-classified scenes into 1-minute cells. As in the 1978 test, precision-calibration files were used to assign pixels from each Landsat scene to a latitude and longitude grid. The number of pixels classified as irrigated cropland was determined and then used to calculate the percentage of the 1-minute cell that was irrigated. In areas of multitemporal coverage, pixels classified as irrigated on both dates were counted only once in determining the percentage irrigated for 1-minute cells.

Aggregation of the pixel data into 1-minute cells provided the first opportunity to view the classification of irrigated cropland for the entire High Plains. Immediately, inconsistencies in the interpretation of irrigated cropland between adjacent scenes became apparent. To correct these errors, all Landsat scenes were redisplayed and the gray-level threshold value and editing were checked and adjusted where necessary.

A review of the classifications revealed that two factors were the cause of differences in the interpretation of irrigated cropland between scenes. First, the gray-level threshold value for many scenes had apparently been set too low, leading to the mapping of nonirrigated land as irrigated cropland. Second, to compensate for the small threshold value, substantial editing had been done, and this editing appeared to be inconsistent.

To improve the classification of irrigated cropland and to minimize the differences in the classification between scenes, new guidelines for interpreting the data were established. First, the data were reinterpreted for contiguous regions having similar cropping practices. This procedure ensured that the same guidelines were used to define irrigated cropland and nonirrigated land. Once the gray-level-threshold value had been set for one scene, it was compared with the threshold value for the adjacent scene. In most cases, the threshold values for scenes from the same region were within a few gray levels of one another. Second, the threshold value for irrigated cropland generally was increased. Previously, the classification of irrigated cropland was maximized by using a small cutoff value to include all pixels in irrigated fields. By raising the cutoff value for irrigated cropland, most border pixels within irrigated fields (pixels within an irrigated field that did not have a lush vegetative canopy and had an appearance similar to nonirrigated land) were excluded. This method of establishing the cutoff for irrigated cropland decreased the editing required to classify nonirrigated land correctly. However, this method did not always solve classification problems. Sometimes within one scene, an established cutoff did not classify all irrigated cropland correctly. In such instances, large areas of the scene were isolated by editing and a different threshold value was used to classify irrigated cropland within those areas.

Using these new guidelines, all 59 Landsat scenes were reinterpreted. As a result, a better transition between scenes and a more consistent classification of irrigated cropland were produced. These data were then reaggregated to 1-minute cells, and the percent irrigated was computed. These data were transferred to the High Plains RASA data base for use with the ground-water flow model.

In addition, the 1-minute-cell data were used to produce a summary of irrigated acreage for counties contained completely or partly within the High Plains (pl. 1). Digitized county boundaries were overlaid on the aggregated data and used to extract the 1-minute cells in each county. The area of a 1-minute cell changes with latitude from about 702 acres in the southern High Plains to about 604 acres in the northern High Plains. Consequently, it was necessary to determine the average area of cells within each county. The acreage irrigated in each county was calculated by multiplying the number of 1-minute cells contained in the county by the average area of the cells.

MAP PRODUCTS

The 1-minute cell data were geometrically corrected to an Albers Equal Area Projection and read directly into the Sci-Tex large-format laser plotter.[2] The Sci-Tex was used to directly generate four color-separation plates (yellow, cyan, magenta, and black) that were then used, along with an additional plate containing the planimetric overlay, to print a final map product of irrigated cropland for the High Plains during 1980 (pl. 1).

ACCURACY

Maps of Phillips and Yuma Counties, Colo., compiled from Landsat digital data and high-resolution data, were compared during the preliminary county evaluation. These results demonstrated the suitability of Landsat digital data for mapping irrigated cropland for one area of the High Plains. However, to adequately assess results obtained from the 1980 mapping, an evaluation of the accuracy of maps compiled from the ratio-classified Landsat scenes was required. A variety of data sources were initially considered for comparison with the irrigated acreage mapped from 1980 Landsat data. However, the only source available that provided consistent data for the 1980 growing season for all areas of the High Plains was the ASCS. The ASCS routinely collects acreage and irrigation information for the principal crops grown in the High Plains. Farm operators voluntarily provide the ASCS with this information to qualify for Federal farm-program benefits. The ASCS county offices are required to conduct a random sample of at least 15 percent of the participants to verify reported information by field check or aerial photography or both.

The resolution (1-minute cells rather than single pixels) and the volume (approximately 174,000 1-minute cells) of the Landsat data posed a challenge for designing a sampling procedure. Time and personnel were the main constraints in designing a procedure for compiling and analyzing the ASCS data.

Based on these constraints, a two-stage sampling procedure for collecting ground data was designed. The procedure incorporated the technique of stratified simple-random sampling at the first stage (counties) and sampling proportional to the estimated acreage of irrigated cropland at the second stage (1-minute cells).

[2]Any use of trade names is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

A number of variables were considered for defining the strata for sampling: climate, soils, crop types, irrigated acreage, and water demand. However, which of these variables—singly or in combination—were related to Landsat classification accuracy was not known. Consequently, a single variable, estimated density of irrigated cropland by county, was selected as the stratification criterion.

Because the 1980 data analysis was in progress while the accuracy evaluation was being designed, the 1978 Census of Agriculture was used to determine the proportion of irrigated acreage within each of the counties in the High Plains. The proportion of irrigated cropland was determined for all counties having at least one-half of their land area within the High Plains. A frequency distribution of the density of irrigated cropland was created using 187 counties. Densities of irrigated cropland in these counties ranged from less than 1 to 61 percent. The frequency distribution of the density data contained logical break points that allowed the 187 counties to be allocated to 6 relatively homogeneous groups or strata. Time and personnel constraints limited data collection to a maximum of 12 to 15 counties. The counties were initially allocated proportional to the within-stratum variance (Cochran, 1977). However, the resulting sample was not well distributed (greater density strata had too few samples), so the procedure was revised to ensure adequate coverage of that stratum. The modified procedure resulted in the selection of 13 counties for sampling (fig. 14 and table 4).

A PPS technique (probability proportional to size; or, in this case, acreage of irrigated cropland) was used to select 1-minute cells for sampling within each of the 13 counties. Thus, the more irrigated cropland a cell contained, the greater the probability of the cell being selected. Although PPS provided a sample of sites that gave a greater probability of selection to cells that were predominantly irrigated, it also provided for selection of some sites that were predominantly nonirrigated. This sampling procedure ensured the estimation of within-county variance of the density of irrigated cropland. Based on past experience in collecting data from ASCS offices, the number of sampling sites (1-minute cells) within each sample county was limited to 50. Once permission was obtained from State Directors of the ASCS to access farm-operator records, appropriate data were obtained from the ASCS offices in the 13 counties selected for evaluation.

ASCS offices record data using the legal description for the State. Data generally are recorded by township, range, and section. The ASCS section data did not exactly coincide with the location of the 1-minute cells selected for sampling. This resulted in a modification

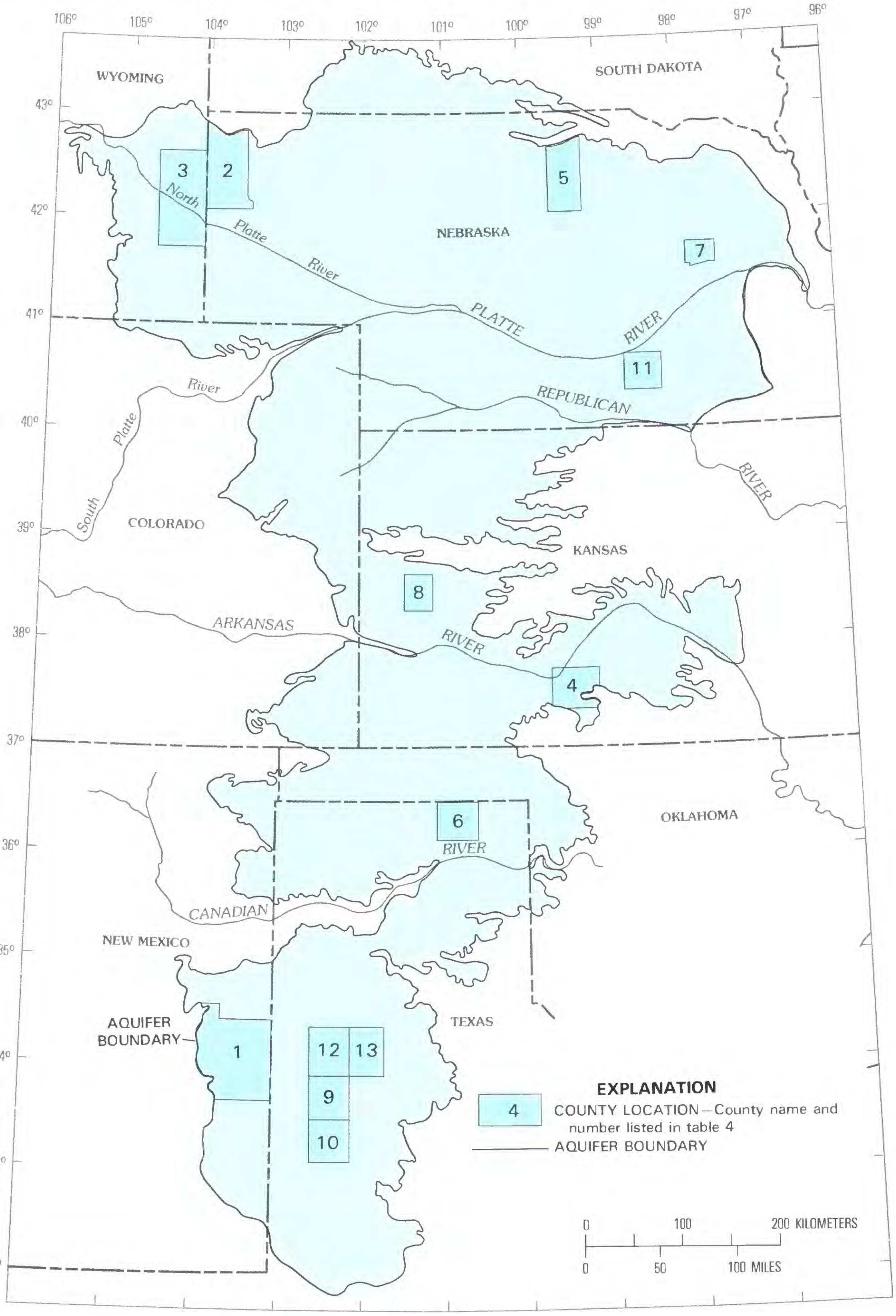

FIGURE 14.—Map showing location of the 13 counties used in the 1980 accuracy assessment.

TABLE 4.—*Allocation of counties to strata used for 1980 accuracy assessment*

Stratum	Percentage irrigated	Number of counties	Stratum mean	Stratum variance	Counties allocated	Location number[1]
1	00–04.99	67	1.88	1.89	Roosevelt	1
					Sioux	2
2	05–14.99	57	9.40	6.50	Goshen	3
					Kiowa	4
					Rock	5
3	15–24.99	32	18.71	10.59	Ochiltree	6
					Platte	7
					Wichita	8
4	25–34.99	12	28.58	5.71	Hockley	9
					Terry	10
5	35–49.99	14	41.50	18.27	Adams	11
					Lamb	12
6	50–61.00	5	58.00	19.98	Hale	13

[1]Location number of county corresponds to county numbers in figure 14.

to the sampling procedure—replacing 1-minute cells with corresponding ASCS sections.

The most time consuming phase of the accuracy evaluation was ensuring the proper registration of ASCS data with Landsat classifications. Each section containing ASCS-sampled data was located on a 1:24,000-scale quadrangle map and digitized. Using the appropriate precision-calibration file associated with the county, Landsat row-and-column coordinates were determined for each section. These coordinates were used to retrieve a band 5 computer-printed, gray-scale map at 1:24,000 scale. An analyst, using a light table, overlaid gray-scale maps on topographic quadrangles so that obvious features (water bodies, major roads, or section line roads) seen on both gray-scale maps and quadrangle maps were aligned. Once aligned, the northwest corner of the section was located on both the gray-scale map and the quadrangle map. Gray-scale maps contained row-and-column coordinates read directly from the CCT, whereas digitized section coordinates were calculated from precision-calibration files. The two sets of coordinates were compared and adjusted to correctly position the section on the gray-scale map. The degree of positioning was dependent on the accuracy of the precision-calibration file: errors typically ranged from 3 to 5 pixels. Individual shift files were created and used to generate mask files for the roughly 400 sections of data obtained from ASCS. These mask files were overlaid on the classified Landsat data, and acreage totals for nonirrigated and irrigated cropland were computed. Likewise, acreage estimates of irrigated and nonirrigated cropland were manually totaled from the ASCS data.

A ratio estimator (Cochran, 1977) was used to compare ASCS and Landsat estimates of irrigated cropland. Theoretically, a ratio estimator is accurate when the variable that is being estimated is proportional to a concomitant variable with a known value. Numerous studies have shown that ground data are significantly correlated with estimates of irrigated cropland derived from the Landsat data (Walker and Sigman, 1982). These ratio estimators (r=ratio of the ground data (ASCS data) estimate of irrigated cropland to the Landsat estimate) for individual sections were averaged to generate mean county ratios ($\bar{r}$). The mean county ratios, multiplied by the Landsat county totals, provided estimates of total irrigated-cropland acreage for the sampled counties. The standard error of the mean county ratio (s.e. of $\bar{r}$), correlation coefficients (ρ) and percentage of ASCS irrigated cropland acreage correctly classified in the 1980 data analysis for each county are shown in table 5. The formulas for calculating these statistics are as follows:

$$\bar{r}= \sum_{i=1}^{n} r_i/n \qquad (1)$$

and

$$\text{s.e. of } \bar{r}= \sum_{i=1}^{n} (r_i-r)^2/n(n-1) \qquad (2)$$

where $\bar{r}$=mean county ratio,
r=ratio of Landsat estimate to ASCS estimate for each sampled section,

TABLE 5.—*Statistical evaluation of the accuracy of irrigated-cropland acreage mapped from 1980 Landsat data for 13 counties in the High Plains*

Stratum	County and State	Mean county ratio ($\bar{r}$)	Standard error (s.e. of $\bar{r}$)	Correlation coefficient (ρ)	Percentage of ASCS[1] irrigated acreage mapped from Landsat
6	Hale, Tex.	1.035	0.200	0.916	97
5	Adams, Nebr.	1.042	.030	.889	96
5	Lamb, Tex.	1.043	.110	.714	96
4	Hockley, Tex.	1.246	.908	.921	80
4	Terry, Tex.	4.516	2.093	.817	22
3	Platte, Nebr.	1.018	.165	.407	98
3	Wichita, Kans.	1.108	.770	.863	90
3	Ochiltree, Tex.	1.313	.153	.883	76
2	Goshen, Wyo.	1.510	.107	.845	66
2	Rock, Nebr.	1.050	.079	.926	95
2	Kiowa, Kans.	1.034	.221	.772	97
1	Sioux, Nebr.	1.149	.952	.947	87
1	Roosevelt, N. Mex.	1.738	.499	.530	58

[1]Agricultural Stabilization and Conservation Service.

n=number of samples in a county, and
s.e. of $\bar{r}$=standard error of the mean county ratio,

and

$$\rho = \sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})/(Sx_i Sy_i)(n-1) \quad (3)$$

where ρ=the correlation of Landsat and ASCS estimates for each sampled section,
x_i=the Landsat estimate of irrigated cropland for each sampled section,
y_i=the ASCS estimate of irrigated cropland for each sampled section,
$\bar{x}$=the mean county Landsat-estimated irrigated acreage,
$\bar{y}$=the mean county ASCS estimated irrigated acreage,
Sx_i=the standard deviation of x for each section, and
Sy_i=the standard deviation of y for each section.

As shown in table 5, two measures of accuracy are available, $\bar{r}$ and ρ. If $\bar{r}$, the mean county ratio, is about 1, minimal bias exists in the Landsat estimate. Ratios greater than 1 indicate underestimates of irrigated acreage compiled from Landsat data relative to estimates compiled from ASCS data, and, conversely, ratios less than 1 indicate overestimates. The other measure of accuracy, ρ, is an indicator of the linearity of the relationship between estimates of irrigated acreage from Landsat and estimates from ASCS data for the county (the closer ρ is to 1, the closer the relationship is to linear). These two measures reveal complementary aspects of accuracy. For example, Terry County, Tex., has a large $\bar{r}$ (4.516, indicating underestimation of irrigated cropland acreage using Landsat data) but a fairly large ρ (0.817). Within Terry County, irrigated cropland acreage was substantially underestimated using Landsat data relative to ASCS-reported acreage. However, fairly good correlation exists between the two estimates, indicating that even though the estimate from the Landsat data is small compared to the ASCS-reported data, the estimate from the Landsat data is consistent for most of the sections in the county and could be adjusted to provide a reliable estimate of irrigated cropland acreage for the county. The value for $1/\bar{r}$ for each county, is the ratio of the irrigated acreage estimated from Landsat divided by the irrigated acreage reported by ASCS. This number is the percentage of ASCS-reported irrigated acreage that was mapped using Landsat (table 5).

In addition to the quantitative results presented in table 5, interpreting and understanding the origin of classification errors are important. Based on the results in table 5, it is evident that classification errors are not associated with a particular stratum or geographic area. Instead, as the following examples will demonstrate, the single most important variable affecting classification accuracy is the availability of suitable Landsat data.

Classification errors for Terry County and Hockley County, Tex., are strikingly different (table 5). These two counties are adjacent and both belong to stratum 4. Within both counties, upland cotton accounts for more than 90 percent of the acreage irrigated. Within Hockley County, 80 percent of the irrigated acreage reported by ASCS was mapped using Landsat, whereas only 22 percent of irrigated acreage was mapped using Landsat in Terry County. Although the two counties are adjacent, they were covered by different Landsat scenes. Because good quality, cloud-free Landsat data were not available for Terry County, obtaining the multitemporal coverage necessary to effectively map irrigated cotton was not possible. Instead, a single date, August 29, 1980, was used to map cotton and other irrigated crops growing in the county. A Landsat color-composite image for part of Terry County is shown in figure 15. Field A was reported as irrigated cotton and is typical of many of the fields in Terry County. Clearly, no evidence of an actively growing crop exists, and, most likely, this late in the growing season the plant canopy had become desiccated and could not, using Landsat data, be distinguished as an irrigated crop.

Within Ochiltree County, Tex., the Landsat estimate of irrigated acreage was 76 percent of that reported to ASCS. Winter wheat and milo (sorghum) make up most of the irrigated acreage within the county. Examination of individual field classifications of these irrigated crops indicated that winter wheat was accurately mapped, but milo generally was not identified. A color-composite Landsat image, from July 14, 1980, for part of Ochiltree County is shown in figure 16. No indication of actively growing crops exists in areas designated by the ASCS as irrigated milo fields (field C in fig. 16). The July 14 Landsat scene was too early in the growing season for milo fields to have attained a dense vegetative canopy.

LANDSAT SCENE (30908-16361) August 29, 1980

FIGURE 15.—Landsat color-composite image for parts of Terry County, Tex.

LANDSAT SCENE (22000-16392) July 14, 1980

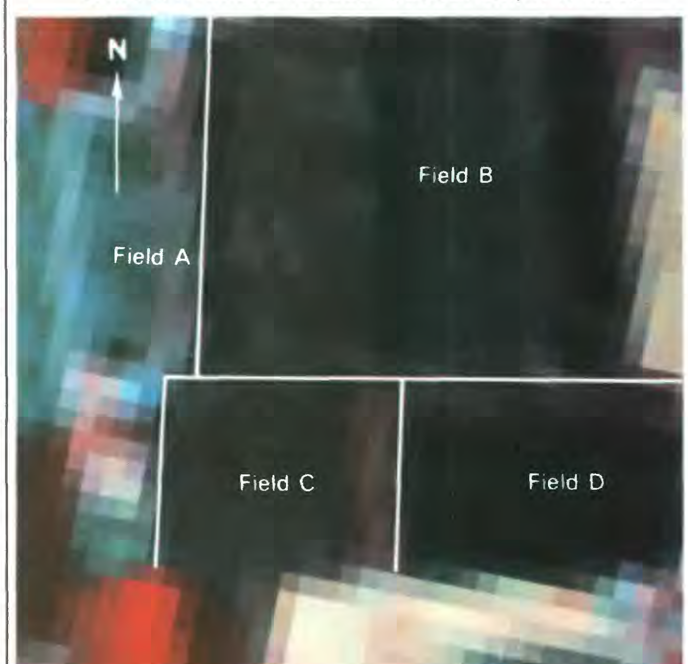

FIGURE 16.—Landsat color-composite image for parts of Ochiltree County, Tex.

LANDSAT SCENE (22018-16391) August 1, 1980

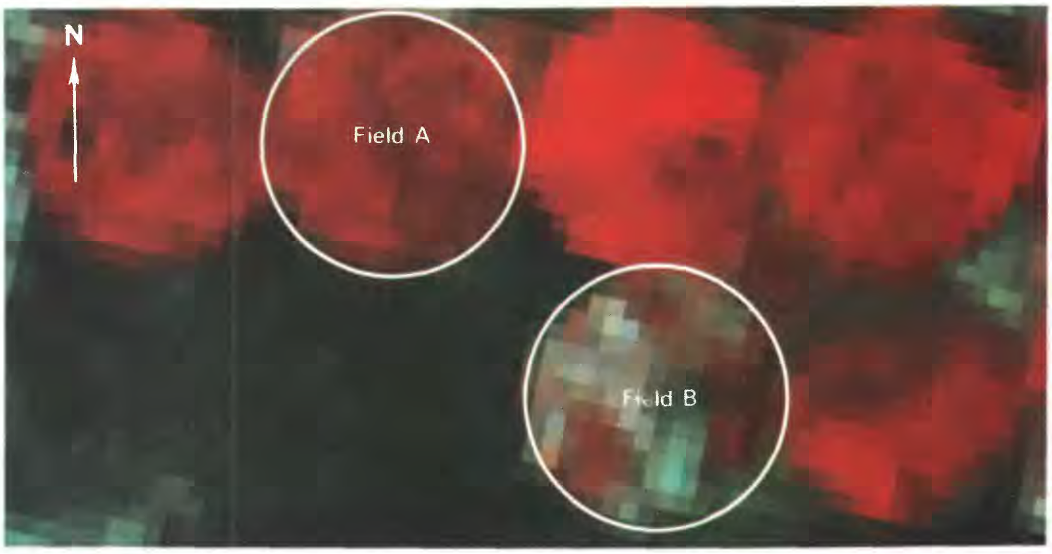

FIGURE 17.—Landsat color-composite image for parts of Kiowa County, Kans.

A color-composite Landsat image from August 1, 1980, covering part of Kiowa County, Kans., is shown in figure 17. Although the classification accuracy (table 5) in Kiowa County was within 3 percent of the ASCS estimate, areas of irrigated hay were difficult to map. Alfalfa and other hay crops commonly occur throughout most counties within the High Plains and are typically harvested more than once during the growing season. In figure 17, field A, irrigated alfalfa, has a lush vegetative canopy and was correctly classified; but, in contrast, field B, which had recently been harvested, was classified as nonirrigated. Based on this example, an early-summer Landsat scene, obtained prior to the first cutting of hay, would be required to correctly map both fields.

Three Landsat color-composite images, from May 13, July 15, and August 29, 1980, for part of Roosevelt County, N. Mex., are shown in figure 18. Irrigated acreage estimated from Landsat for Roosevelt County is only 58 percent of ASCS-reported irrigated acreage. Additionally, little correlation exists (ρ=0.530) between estimates from Landsat and ASCS for individual irrigated fields within the county. Field A was reported as nonirrigated wheat pasture by ASCS but was mapped from Landsat as irrigated on the two summer dates, July 15 and August 29, 1980. However, this same field appears to be fallow on the May 13 Landsat scene. Two other ASCS-designated nonirrigated fields, B and C, appear to be irrigated on the August 29 Landsat scene. Field D was reported as nonirrigated by ASCS and was mapped correctly by Landsat. The cause of the discrepancies between the ASCS and Landsat field designations in Roosevelt County could not be determined.

The lack of suitable Landsat data on or near optimal dates for identifying various irrigated crops resulted in the loss of accuracy in mapping some areas of the High Plains. However, in the context of mapping the entire High Plains, this problem was confined to small areas. Overall, the results obtained in the accuracy evaluation show that digital analysis of Landsat data can be used to provide reliable estimates of irrigated cropland acreage for an area as large and diverse as the High Plains.

However, for both the 1978 test and the 1980 analysis, data were acquired from two operational Landsat satellites, and repeat coverage was available every 9 days throughout the growing season. In the future, if only one satellite is operational, repeat coverage will be once every 18 days rather than once every 9 days. Given potential cloud cover, one satellite may not be able to provide the necessary coverage to obtain a complete inventory of irrigated cropland, which would adversely affect the reliability of estimates of irrigated acreage made from Landsat data.

In summary, the accuracy evaluation helped pinpoint some of the specific problems associated with the identification and interpretation of irrigated cropland in the High Plains using Landsat-digital data. Stratification of the data base was beneficial for decreasing the sample size and evaluating the accuracy of mapping large and contiguous areas (counties). However, development of a stratification incorporating such factors as soils, crop types, irrigation types, and precipitation data

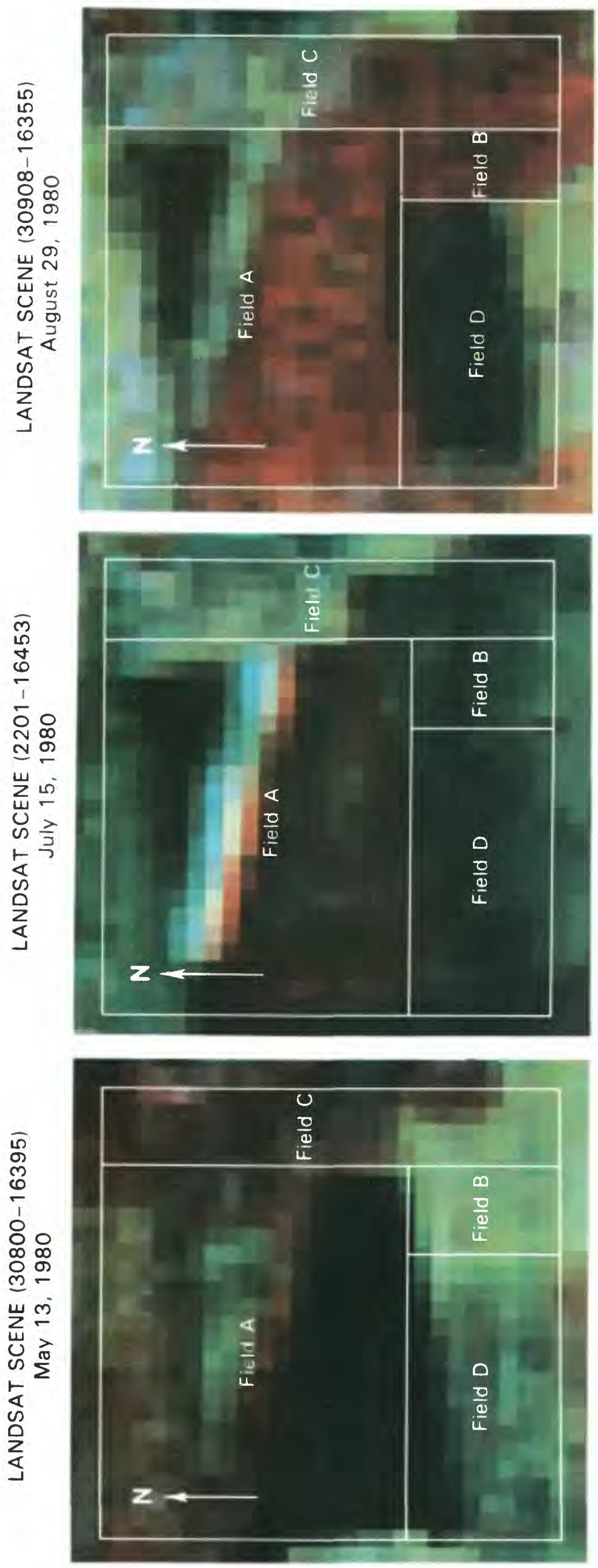

FIGURE 18.—Landsat color-composite image for parts of Roosevelt County, N. Mex.

would be necessary to make more definitive statements about how these factors can affect the accuracy of mapping irrigated cropland using Landsat-digital analysis.

WATER-USE DETERMINATION

Tabulations of irrigated cropland, nonirrigated cropland, and rangeland interpreted from Landsat data were used in conjunction with other geohydrologic data to estimate hydrologic parameters for the ground-water flow model of the High Plains aquifer. The purpose of mapping irrigated acreage using 1980 Landsat data was to compute the volume of ground water pumped for irrigation. Sampled measurements of ground water pumped for irrigation were used to compute the average depth of water applied to each of the major irrigated crops grown on the High Plains during 1980. Relationships were established between depth of application, computed from sampled data, and the irrigation requirement of the crops, estimated using consumptive-use formulas. The relationships derived from the sampled data were used to estimate the depth of applied irrigation water for all areas of the High Plains during 1980. Estimates of depth of application were subsequently combined with irrigated acreage data to provide estimates of the volume of ground water pumped.

Nonirrigated cropland and rangeland acreage data, compiled from the analysis of 1978 Landsat data, provided additional information that helped to allocate estimates of recharge to the aquifer. Acreage information on nonirrigated cropland and rangeland was combined with information on precipitation, temperature, soils, and topography to help develop and allocate estimates of recharge for use in the ground-water flow model.

The following discussion summarizes the procedures used to estimate the volume of water pumped and the irrigation water-use estimates that were derived for areas of the High Plains during 1980. A detailed discussion of the procedure used and an analysis of the results obtained is contained in Heimes and Luckey (1983). The program to determine the volume of ground water pumped for irrigation in areas of the High Plains was established in two phases. A 1979 pilot test was conducted to develop procedures and test equipment. The 1979 test was followed by the 1980 sampling program that was used to develop estimates of ground water pumped for irrigation.

SAMPLING OF GROUND WATER PUMPED

1979 PILOT TEST

The 1979 pilot test was conducted to (1) develop a statistical approach to sample ground water pumped for irrigation, (2) test instrumentation and develop procedures for measuring the ground water pumped from selected irrigation wells, and (3) develop relationships between the ground water pumped and acreage irrigated. Two test areas (fig. 19) were selected for use in the 1979 pilot test. The eight-county test area, which also was used to test mapping approaches, was located in the northern High Plains (fig. 5). A second two-county test area was located in the southern High Plains and consisted of Hockley and Lamb Counties, Tex.

The volume of ground water pumped was measured at about 250 randomly selected irrigation wells located in the two test areas. The volume pumped from each well was computed by multiplying the pumping rate by the total time of pumping. Several types of portable flowmeters for measuring pumping rate, and one timing device to monitor total time of pumping, were tested for suitability and accuracy. The depth of water applied (volume pumped divided by the acreage irrigated) was calculated for various crop types, irrigation systems, and climatic zones to determine which of these factors would be important in estimating and extending sampled data to other areas of the High Plains.

The results of the 1979 pilot test are presented in detail in Heimes and Luckey (1980). The 1979 test provided the necessary information for the design of the sampling program that was used in conjunction with irrigated-acreage measurements from Landsat to estimate the volume of ground water pumped in the High Plains during 1980. The development of mapping procedures in the preliminary county test and the analysis of 1978 Landsat data were done concurrently with the 1979 pilot test.

1980 SAMPLING

The 1980 sampling program was designed to provide the High Plains RASA project with current data on ground water pumped for irrigation for selected areas in the High Plains. All or parts of 15 counties located in various parts of the High Plains were selected for sampling during the 1980 irrigation season (fig. 20). A total of 480 individual sampling sites, each site containing one or more irrigation wells, were selected in these 15 counties. The number of sampling sites that were selected in each county or pair of counties is shown in table 6. The county sampling areas were chosen to provide a representative cross section of irrigation systems, crop types, and physical factors such as geology, hydrology, soils, and climate occurring within the High Plains region. Individual sampling sites, within each of the county sampling areas, were selected randomly.

Discharge, time-of-operation, crop-type, and crop-acreage data were monitored at each of the sampling

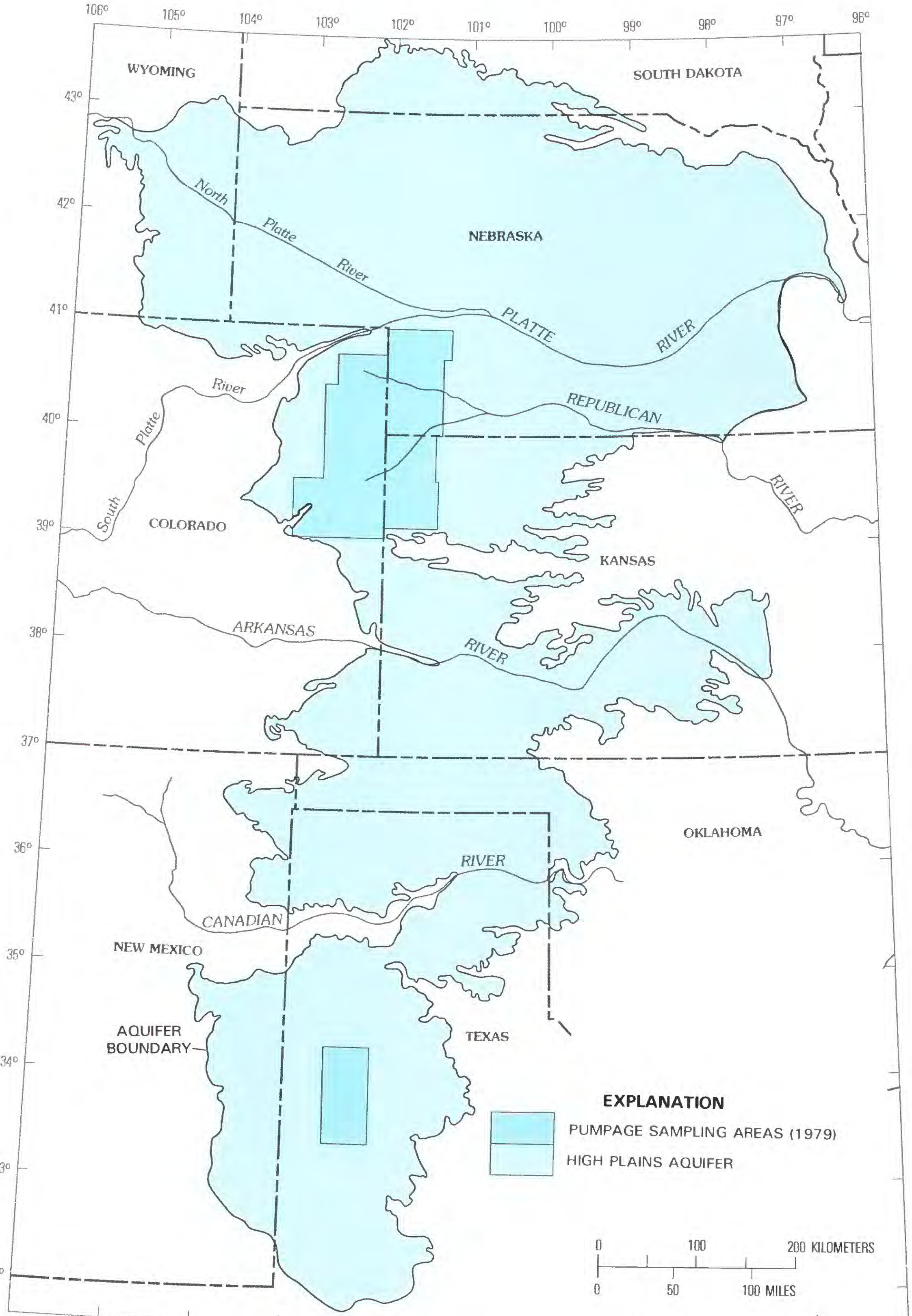

FIGURE 19.—Map showing location of test areas used for the 1979 pilot test.

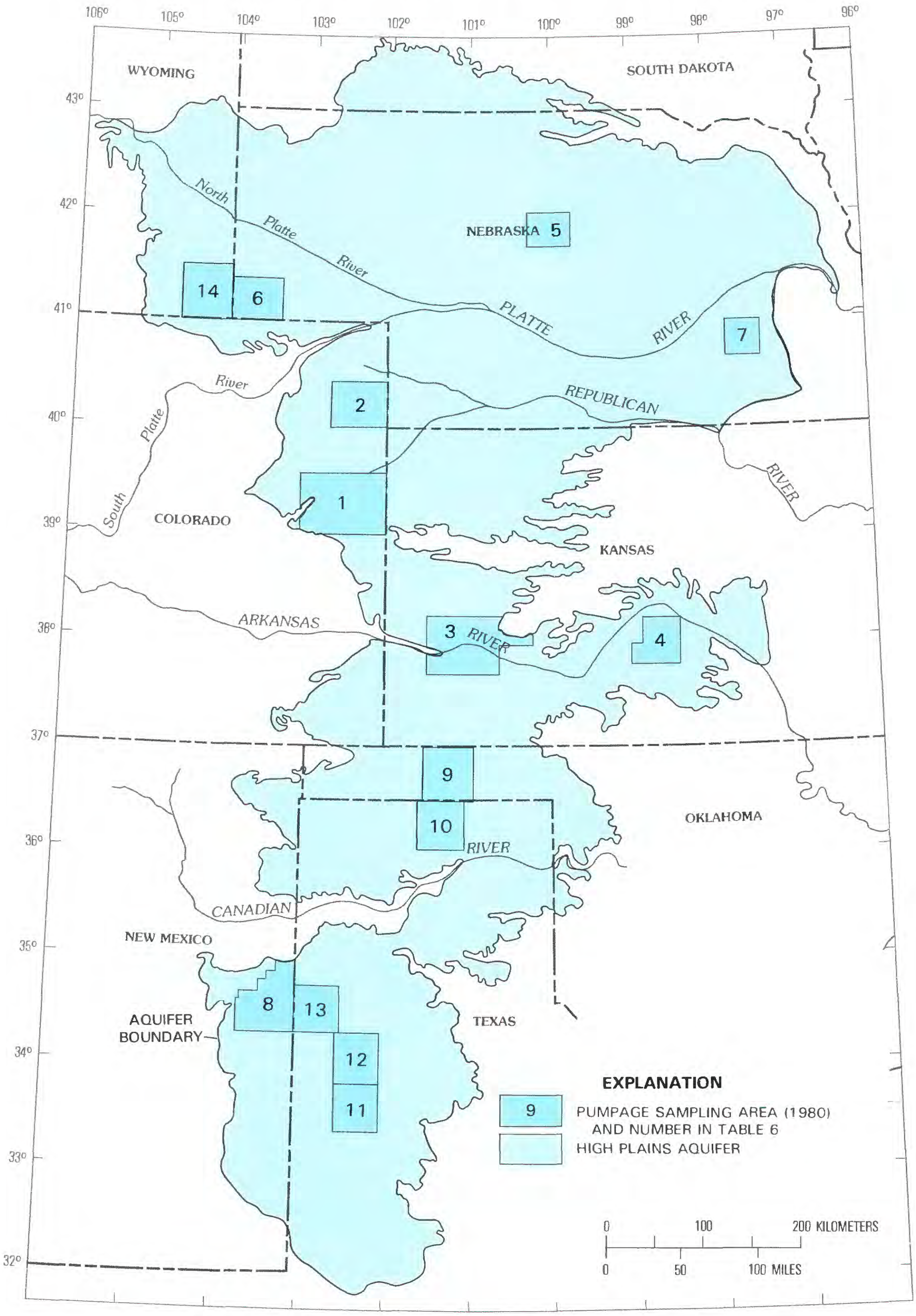

FIGURE 20.—Map showing location of 1980 pumpage-sampling areas.

TABLE 6.—*Distribution of 1980 pumpage-sampling sites in the High Plains*

Location of area	Location number in figure 20	Number of sites
Kit Carson County, Colo.	1	25
Northern Yuma County, Colo.	2	40
Finney and Kearny Counties, Kans.	3	50
Stafford County, Kans.	4	50
Blaine County, Nebr.	5	50
Kimball County, Nebr.	6	20
York County, Nebr.	7	50
Curry County, New Mex.	8	16
Eastern Texas County, Okla.	9	15
Hansford County, Tex.	10	35
Hockley County, Tex.	11	20
Lamb County, Tex.	12	20
Parmer County, Tex.	13	59
Eastern Laramie County, Wyo.	14	30
Total		480

sites. These data were used to compute the average depth of water applied (application), in inches for each site. The next step was to use the application data compiled for each of the county sampling areas to estimate application for the remainder of the High Plains. Climate, soils, crop distribution, and irrigation practices change significantly from one area to the next in the High Plains, so a procedure that would take these factors into account had to be developed for extending sample data to other areas.

ESTIMATES OF WATER USE

The method chosen to estimate depth of application for unsampled areas of the High Plains was based on a ratio between sampled application and calculated irrigation demand (application-demand ratio). Irrigation demand (estimated depth of irrigation water required by a crop during the growing season) was calculated using the Blaney-Criddle formula (U.S. Department of Agriculture, 1967), for all major irrigated crops growing on the High Plains. Application-demand ratios developed in the sampled counties, for each crop, were used to estimate application for unsampled areas. The High Plains was subdivided into areas of 1° lat×1° long (1° cells) for calculating application estimates. A weighted-average application was calculated for each 1° cell using the proportions of the various irrigated crops growing in each cell as the weighting factors. Irrigation-demand calculations take into account the changes in climate and soils from one cell to the next. Changes in the distribution of crop types between cells are accounted for by estimating the proportions of crops grown in each county (Martinko and others, 1981) and then aggregating county data into 1° cells. Differences in irrigation and cropping practices are accounted for by the application-demand ratios for individual crops growing in the various sampling areas.

The weighted-average application for each 1° cell located in the High Plains was multiplied by the irrigated acreage for that cell to obtain the volume of ground water pumped for irrigation. Areas of riparian vegetation that had been classified as irrigated cropland were manually deleted during the analysis of the Landsat data. However, agricultural areas irrigated by surface water could not be separated from areas irrigated by ground water during analysis of the Landsat data. Consequently, for areas that contained a significant proportion of surface-water irrigation, the irrigated acreage compiled from Landsat analysis was adjusted to reflect only acreage irrigated by ground water.

The acreage irrigated by surface water was obtained from the Census of Agriculture and from State water-resources agencies. These data were compiled for cells measuring 10 minutes of latitude by 10 minutes of longitude (10-minute cells) and stored in the High Plains RASA computer data base. The surface-water irrigated acreage for each 10-minute cell was subtracted from the corresponding 10-minute cell aggregations of irrigated acreage mapped from Landsat to obtain the acreage irrigated by ground water. Data on acreage irrigated by ground water in 10-minute cells were aggregated into 1° cells and multiplied by the weighted application estimates for the cells to calculate the volume of ground water pumped. Estimates of the volume of ground water pumped in 1° cells were further aggregated to provide estimates of ground-water pumpage for each State in the High Plains.

The estimated acreage irrigated and the volume of ground water pumped for irrigation in the High Plains of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming are summarized in table 7. The estimated total volume of ground water pumped for irrigation during 1980 in the High Plains was 17,980,000 acre-ft applied to 13,700,000 acres. Three States (Kansas, Nebraska, and Texas) accounted for about 87 percent of the total volume of

TABLE 7.—*Irrigated acreage compiled from Landsat data, and estimated volume of ground water pumped for irrigation in areas of the High Plains during the 1980 growing season*

[Values rounded to nearest thousand]

State	Irrigated acreage from Landsat data (acres)	Volume of ground water pumped (acre-feet)
Colorado	849,000	1,023,000
Kansas	2,810,000	4,130,000
Nebraska	5,273,000	6,395,000
New Mexico	325,000	519,000
Oklahoma	389,000	540,000
South Dakota	26,000	33,000
Texas	3,878,000	5,170,000
Wyoming	150,000	170,000
Total	13,700,000	17,980,000

ground water pumped in the High Plains. Texas, which accounts for about 20 percent of the area in the High Plains and 29 percent of total volume of ground water pumped, is the most densely developed area. South Dakota, which accounts for less than 3 percent of the area and about 0.1 percent of the total volume of ground water pumped, virtually is undeveloped.

SUMMARY AND CONCLUSIONS

Development and application of the ground-water flow model for determining the responses of the aquifer to agricultural development required current information on the volume and distribution of pumpage for irrigation. Maps and tabular information of irrigated acreage were required for computing estimates of irrigation-water use. The initial phase of the study, the preliminary county test, indicated that digital analysis of Landsat data provided a source of current information about irrigated cropland that could be used in conjunction with data collected from physical sampling of irrigation wells. Additionally, the digital format of the data was compatible for use with the High Plains RASA data base.

Designing an efficient technique for processing the large quantity of data required to map irrigated cropland for the High Plains was necessary, so the following two-step approach was devised:

1. A test was conducted using 1978 Landsat data to develop and evaluate the procedures necessary to map irrigated cropland for the High Plains.
2. 1980 Landsat data were used to map irrigated cropland for the entire High Plains using analysis techniques developed as a result of the 1978 test.

The 1978 test was undertaken to develop the procedures required to process and analyze large volumes of Landsat data, and to evaluate the effects of diverse environmental conditions and cropping practices on the results obtained from digital analysis of the Landsat data. Cluster analysis of summer data from 35 Landsat scenes provided acreage estimates for irrigated and nonirrigated cropland, rangeland, and several other land-use categories for most of the High Plains. Nonirrigated cropland and rangeland acreages provided information that could be used to help estimate recharge to the aquifer. During this phase of the project, software was developed to aggregate Landsat pixel data into 1-minute cells for use in the High Plains RASA data base. The use of the 1-minute cells was an effective approach for handling the large volumes of pixel data that were analyzed. This approach provided an efficient method for combining the individual Landsat classifications into a single comprehensive data set.

Completion of the 1978 test led to the modification of a number of procedures for analyzing 1980 Landsat data. Because only acreage information about irrigated cropland was needed for 1980, cluster-analysis techniques were abandoned and a simplified band-ratio technique was adopted. The software required to calculate a band ratio from the Landsat data was installed on a minicomputer and eliminated the use of costly mainframe computer facilities for most phases of processing. Ratio classifications were produced for 59 Landsat scenes that provided acreage estimates for both spring and summer irrigated crops grown during 1980. To aid in the interpretation of the ratio classifications, a fast and efficient interactive display and editing package known as the CIE was developed. After interpretation, Landsat pixel data were aggregated to 1-minute cells, representing the density of irrigated acreage, for use in the High Plains RASA data base.

An accuracy evaluation of the 1980 Landsat analyses demonstrated that estimates of irrigated cropland acreage derived from Landsat digital data are reliable throughout most of the High Plains. Classification errors were not correlated with geographic location or density of irrigated cropland, but generally were associated with the lack of suitable Landsat data for the recommended optimal dates. This affected the analysis in Terry County, Tex., where the optimal Landsat dates for mapping cotton were not available because of cloud cover. Consequently, irrigated-acreage estimates from Landsat were only 22 percent of the ASCS reported acreage for Terry County.

Conversely, for those counties used in the accuracy evaluation which had the recommended dates of Landsat coverage, acreage estimates were at least 90 percent of irrigated acreage reported by ASCS. Given the availability of suitable Landsat data, results obtained from the accuracy evaluation have validated the use of Landsat data and digital-analysis techniques for providing estimates of irrigated cropland for an area as large and diverse as the High Plains.

Estimates of irrigated cropland, nonirrigated cropland, and rangeland obtained from both 1978 and 1980 Landsat data were transferred to the High Plains RASA data base. Irrigated and nonirrigated cropland and rangeland acreage data were combined with other geohydrologic information to estimate irrigation-water use and to allocate recharge for use in the ground-water flow model. Irrigated-cropland-acreage estimates were used in conjunction with estimates of the depth of irrigation water applied to compute the volume of ground water pumped in the High Plains for the 1980 growing season.

The size of the area (174,000 mi^2) precluded sampling irrigation water applied in all parts of the High Plains. Instead, estimates of irrigation water applied were computed, for all areas of the High Plains, using ratios that were established between sampled irrigation applications and irrigation demands calculated using the Blaney-Criddle formula. The estimated total volume of ground water pumped in the High Plains for the 1980 growing season was 17,980,000 acre-ft applied over 13,700,000 acres. Three States—Kansas, Nebraska, and Texas—accounted for about 87 percent of the total volume pumped.

Estimates of irrigation water applied were successfully combined with Landsat-derived irrigated acreages to provide timely information on water use that was not available from other sources. The relationships established between sampled irrigation application and computed irrigation demand at selected sites proved to be an effective way to develop estimates of irrigation water applied for all areas of the High Plains.

Irrigation techniques, crop varieties, and cropping practices are changing rapidly in many areas as a result of increased irrigation costs and decreased water availability. Prior to the development of a plan to effectively manage the water resources in these areas of agricultural importance, current and reliable estimates on the volume and the distribution of water use are essential. These estimates of water use can then be combined with other geohydrologic data in a ground-water flow model to evaluate the effects of various management strategies prior to their implementation. The Landsat-mapping and water-use-sampling techniques used in this study represent an approach for providing timely information on irrigation water use in the Western United States.

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GLOSSARY

Algorithm. A series of well-defined steps used to accomplish a specific process, for example, a classification algorithm; an algorithm may be in the form of a word description, explanatory note, diagram, or labeled flow chart.

Center pivot. An automated sprinkler irrigation system that irrigates in a circular pattern, pivoting about the center point.

Color composite. A color image produced by assigning a color to a particular spectral band. In Landsat data, ordinarily blue is assigned to band 1 (0.5–0.6 μm), green to band 5 (0.6–0.7 μm), and red to band 6 (0.7–0.8 μm) or band 7 (0.8–1.1 μm), to form an image approximating a color-infrared photograph.

Color-infrared photographs. Photographs using film that is sensitive to energy in the visible and near-infrared wavelengths, generally from 0.4–0.9 μm; usually used with a minus-blue (yellow) filter that results in an effective film sensitivity of 0.5–0.9 μm. Color-infrared film is especially useful for detecting changes in the condition of the vegetative canopy that commonly are manifested in the near-infrared region of the spectrum; color-infrared film is not sensitive in the thermal-infrared region and, therefore, cannot be used as a heat-sensitive detector.

Clustering. As used in this study, refers to the process of partitioning multispectral Landsat digital data into a number of classes or clusters, with each cluster containing groups of pixels that have similar spectral values. A form of multivariate analysis.

Crop phenology. A description of planting and harvesting dates (crop calendar) and other stages of development of a given crop during various times in the growing season. Dates vary with location and climatic conditions.

Depth of application. The average depth, in inches or feet, of irrigation water applied to a particular field for the growing season.

Digital interpretation. The process of computer manipulation and classification of digitally formatted images (Landsat-digital data). For this study, Landsat-digital data were classified or grouped into data sets (clusters) with similar characteristics or enhanced by calculating band ratios using the computer. An analyst interactively related these data sets to land-cover classes.

Digital value. A numerical value that represents the intensity of reflected energy measured from a surface area represented by a pixel and a given spectral band.

Gray level. Tonal gradations from black to white that correspond to or represent digital values.

Gray-scale maps. Line-printer or electrostatic-plotter maps portraying various features or attributes as different shades of gray (gray levels).

Ground data. Supporting data collected on the ground and information derived from those data that serve as an aid to the interpretation of Landsat or other remotely sensed imagery. Ground data also can be used to evaluate the accuracy of interpretations derived from remotely sensed data.

Ground-water flow model. A digital representation of an aquifer system that computes water levels in the aquifer using a two-dimensional equation (in this study) that describes the horizontal ground-water flow.

Herbaceous. Leafy vegetation that has little or no woody tissue and usually dies back at the end of the growing season.

Irrigation demand. The depth of irrigation water required by an individual crop growing in a given area under specified climatic conditions. Irrigation demand, for the purposes of this report, is computed on a monthly basis by subtracting monthly effective precipitation from the estimated monthly consumptive use of a crop based on the Blaney-Criddle formula.

Landsat MSS bands (channels). Refers to the four spectral bands covered by the Landsat multispectral scanner: band 4 (0.5–0.6 μm, green), band 5 (0.6–0.7 μm, red), band 6 (0.7–0.8 μm, near infrared), band 7 (0.8–1.1 μm, near infrared).

Landsat data. Refers collectively to the Landsat multispectral-scanner digital data for each of the four visible and near-infrared spectral bands.

Landsat image. A color-composite image produced by assigning primary colors to three spectral bands of Landsat multispectral-scanner data. Blue is assigned to band 4, green to band 5, and red to band 7.

Landsat multispectral scanner (MSS). An optical-mechanical scanner that uses an oscillating mirror to continuously scan perpendicular to the spacecraft trajectory. Radiation is sensed simultaneously by an array of six detectors in each of four Landsat bands (see Landsat MSS Bands).

Landsat scene. The area on the ground covered by one set of Landsat multispectral-scanner data for a particular date. A Landsat image visually depicts the area covered by a single Landsat scene.

Multispectral. Two or more spectral bands.

Multitemporal. Of or pertaining to more than one time or period; as multitemporal analysis or observations; indicating studies, usually of the same area (multitemporal Landsat scenes) or object, conducted at specific time intervals.

Pixel. A data element having both spatial and spectral aspects; the spatial variable defines the apparent size of the resolution cell (the area on the ground represented by the data values), and the spectral variable defines the intensity of the spectral response for that cell in a particular channel; term derived from picture element.

Recursive. Relating to a procedure that can repeat itself indefinitely or until a specified condition is met.

Spectral band. An interval in the electromagnetic spectrum defined by two wavelengths, frequencies, or wave numbers.

Spectral class (cluster). A group of pixels that have similar spectral values (see clustering).

Spectral data (values). Refers to the data collected for a specific wavelength or frequency range, such as data collected by a particular band of the Landsat-multispectral scanner. The values correspond to the intensity of reflected or emitted energy measured for a given spectral band (digital values).

Spectral statistics. The mean vector and covariance matrix of digital values for a spectral class.

Visual interpretation. The act of examining photographic images for the purpose of identifying objects and judging their significance; also called photointerpretation or image interpretation.

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