Assessments of groundwater management programs in the High Plains region are often limited by inadequate information on water demand and water quality. Although an extensive network of metered wells and sampling of water quality would provide the spatial and temporal information necessary for better management of groundwater, economic and political factors preclude such approaches. Meter installation and associated retrofitting, for example, would cost several million dollars in each of the High Plains states (Nellis 1987). Additional costs of regular meter maintenance and collection of data on water use and quality make these labor-intensive approaches impractical, and irrigators frequently resist attempts by policy makers to require such data collection as an invasion of their right to manage water as they choose. But because comprehensive information about water demand and water quality is critical to water resource planners, we need to explore alternative monitoring methods. Successful techniques include the use of remote sensing and geographic information systems.

AN INTRODUCTION TO REMOTE SENSING

Several researchers (Heines and Luckey 1980; Loveland and Johnson 1983; and Nellis 1987) have focused on integrating remotely sensed, land-cover data and water-response rates by cover type to estimate water use. Past studies (e.g., Astroth et al. 1990) illustrated the general advantage of remote sensing in providing land-cover data–crop type (e.g., wheat) and irrigation method (e.g., center pivot)–for water resource investigations because the information can supply water estimates for individual fields within geographically large areas in a cost-effective manner when the proper system is used. Thus, remote sensing can provide synoptic information about water use to assist the water manager in making decisions.

Generally, most of the remote sensing research associated with groundwater monitoring in the High Plains has followed one of three
approaches. Initial investigations provided direct measurements of irrigation acreage for water resources planning programs (Poracsky 1979). Later research focused on either a two- or a three-step procedure for predicting groundwater use (e.g., acre-feet of water used for a specific area) (Nellis 1987). In the two-step sequence, the remote sensing data were first classified into categories of land cover or land use; land cover was differentiated by irrigated or nonirrigated and by specific, irrigated crops. Then, a representative value of the hydrologic or water-related parameter for that land-use category was estimated through a mathematical model. Some studies have since added to this two-sequence approach by developing a direct relationship between the land-cover/water parameters and other landscape characteristics to predict a third characteristic of the water management system such as the energy requirements for irrigation (Loveland and Johnson 1983). For example, land-cover/water parameters have been linked with the characteristics of slope and of distance from the water source to assess requirements for energy pumpage.

MEASURING IRRIGATED ACREAGE WITH REMOTE SENSING

Several investigators have been successful in determining irrigated and nonirrigated crop areas using aerial photography and Landsat imagery. Such inventories are useful to the regional, state, and federal water-resource managers who need accurate information on the dynamics of irrigated acreage. Nellis (1987), for example, employed color infrared photography with a spectral sensitivity from 0.5 to 0.9 micrometers (sensitivities to green, red, and near-infrared earth radiation with high hue values representing irrigated wheat) in northwest Kansas to map irrigated and nonirrigated crops successfully as part of an initial investigation into predicting water demand (see illustration, p. 147). Color infrared photography (sensitive to the near-infrared) has also been used to monitor crop conditions and uniformity of water distribution in irrigated areas of the High Plains (Bye 1987). This type of photography is more widely available than thermal infrared imagery and its costs per unit area are lower.

Hoffman (1983), Kolm and Case (1984), and others used Landsat imagery to identify and locate land irrigated by center pivot systems in the High Plains of Nebraska and South Dakota. The current Landsat satellite has two sensors on board: a multi-spectral scanner and a thematic mapper. These provide spatial and spectral resolutions relative to monitoring water resource/irrigation agriculture (Table 7.1). The Landsat
High-altitude infrared photograph of irrigated wheat in the High Plains of northwest Kansas.

the thematic mapper has greater utility than the multispectral scanner for more detailed mapping of irrigated crops because of its increased spatial and spectral resolution.

In Texas, integrating both aerial photography and satellite remote sensing has proven useful for mapping irrigated areas. The Texas Natural Resources Information System, which combines remote sensing and geographic information systems, provides water managers in Texas with additional information on irrigated cropland and the dynamics of cropland changes (McCulloch 1983).

Studies by Poracsky (1979) and others indicate that the Landsat multispectral scanner band 2 (Landsat thematic mapper band 3) is useful for mapping irrigated land in Kansas because actively growing vegetation reflects a high level of red light. Poracsky employed the Landsat imagery
Table 7.1. Landsat Sensor Spatial, Spectral Resolutions, and Utility for Water Resource Monitoring

<table>
<thead>
<tr>
<th>Spatial Band Resolution</th>
<th>Spectral Resolution</th>
<th>Utility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multispectral sensor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>79 meters</td>
<td>0.5-0.6um(green)</td>
</tr>
<tr>
<td>2</td>
<td>79 meters</td>
<td>0.6-0.7um(red)</td>
</tr>
<tr>
<td>3</td>
<td>79 meters</td>
<td>0.7-0.8um(near IR)</td>
</tr>
<tr>
<td>4</td>
<td>79 meters</td>
<td>0.8-1.1um(near IR)</td>
</tr>
<tr>
<td>Thematic mapper</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>30 meters</td>
<td>0.45-0.52um(bl-green)</td>
</tr>
<tr>
<td>2</td>
<td>30 meters</td>
<td>0.52-0.60um(green)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>30 meters</td>
<td>0.63-0.69um(red)</td>
</tr>
<tr>
<td>4</td>
<td>30 meters</td>
<td>0.76-0.90um(near IR)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>30 meters</td>
<td>1.55-1.75um(near IR)</td>
</tr>
<tr>
<td>6</td>
<td>120 meters</td>
<td>10.4-12.9um(far IR)</td>
</tr>
<tr>
<td>7</td>
<td>30 meters</td>
<td>2.08-2.35um(mid IR)</td>
</tr>
</tbody>
</table>

To produce maps of six Kansas High Plains counties. A statistical analysis of accuracy derived from a detailed study of Finney County indicated a mapping accuracy of 85 to 99 percent (depending on the particular crop) and an aggregated areal statistical accuracy of 99 percent for the three major crops: wheat, corn, and sorghum.

Although techniques of visual interpretation are useful for many studies that identify irrigated lands in the High Plains, Kolm and Case (1984) discovered that ratioed classifications of logarithmically stretched images based on the Landsat multispectral band 4/band 2 ratio and on an unsupervised-supervised (decision-maker assisted) smoothing technique of multiple-band images produced the best interpretation in the High Plains of South Dakota. Using this approach, they found that irrigated alfalfa was more effectively identified and mapped using May Landsat imagery, but irrigated corn and soybeans were most easily mapped using an August Landsat image.

In his research in western Kansas, Nellis (1987) used a combination of ratioing and supervised classification to delineate irrigated cropland. Supervised classification incorporates ground-reservation information in the classification procedures to enhance accuracy. A two-band scattergram of band 4 relative to band 2 of Landsat multispectral scanner data illustrates the utility of this combination for classifying irrigated cropland in western Kansas (Figure 7.1). Band 4 values are based on the intensity of reflectance by the crop in infrared light; band 2 shows the level of reflective response by the crop in the red-light region of energy. To further
refine the ratioing technique Nellis applied a supervised-maximum-likelihood classifier to all four Landsat multispectral bands. This procedure allowed for an analysis of variance and a correlation of the irrigated cropland category’s spectral-response patterns when classifying an unknown pixel (grid location in the raster-based Landsat data file). The resulting classification proved to be 80 to 90 percent accurate depending on the crop. Baumgardner (1983) achieved similar results in his research in the Texas High Plains.

ASSESSING CROP-WATER NEEDS
WITH REMOTE SENSING

Measurement of crop canopy temperatures, using an aerial thermal scanner, has also proven useful to irrigators and to regional water managers for acquiring information about soil water status in the High Plains, which can be useful for determining the water needs of irrigated and nonirrigated crops. In Nebraska, Blad et al. (1981) employed thermal infrared remote sensing to study sorghum and corn. The study defined the relationship between crop canopy temperatures and moisture stress in plants and evaluated factors affecting canopy temperatures. The thermal scanner detected radiation in the 8.7 to 11.5 micrometer range of electromagnetic energy (far-infrared region). Blad found that nonirrigated sorghum was a few degrees warmer than irrigated sorghum from mid-
afternoon to late evening. In addition, corn under stress was as much as 12.8° C (55° F) warmer than nonstressed corn in the afternoon. Such findings offer significant potential for assessing the conditions of irrigated and nonirrigated crops; they also provide information that could lead to more effective management of irrigation water by determining the water needs of irrigated crops through the variations in irrigated crop-canopy temperatures.

A similar approach using thermal infrared remote sensing was developed by the Earth Resources Data Corporation (1985) to estimate water requirements of crops, water-distribution uniformity, mechanical failures, soil moisture, and water-use scheduling. The research was based on the functions of plant physiology. High temperatures indicate stress because plants conduct water and nutrients through their vessels and exchange carbon dioxide through their leaf surfaces. If the plant is stressed from too little water or from disease, insects, or salts in the soil, the movement of water and nutrients and the exchange of gases is reduced. Stressed plants usually transpire less than unstressed plants. The leaf temperatures in crops not receiving adequate irrigation water, for example, remain high because they lack the cooling effect of full transpiration.

A model developed by Van Bavel (1984) for use in the Texas High Plains combines the information obtained from microwave remote sensing (the moisture in the top 2 inches of the soil) with moisture-distribution patterns for particular types of soil. The model also considers moisture loss by evaporation and moisture gained from precipitation. Such information would be of significant value to farmers and to irrigation-management specialists who are required to make decisions regarding crop water needs and for increasing the efficiency of groundwater use.

From a broader regional perspective, the National Oceanic and Atmospheric Administration (NOAA) satellite has been used in Nebraska to assess vegetative conditions (Peters and Greegor 1987) as they relate to crop water needs. Although designed as a meteorological data collector, two of the five bands on board the satellite are useful for land-resource investigations: Channel 1 records visible red light, and channel 2 records near-infrared energy from the earth’s surface. Since red light is absorbed and near-infrared energy is highly reflected by living vegetation, a calculation of channel 2 minus channel 1 divided by channel 2 plus channel 1 has proven useful for indicating the condition of living vegetation. This calculation highlights the degree of live biomass that can then be correlated with irrigated cropland. The resulting data have proven useful for anticipating groundwater demands associated with irrigation based on the condition of the vegetation as determined by the NOAA satellite. As
with other satellite data, NOAA data is readily available to the general public and would be of value to regional water resource managers.

ESTIMATING WATER DEMAND USING REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEMS

Data derived from remote sensing of irrigated cropland can be integrated with other data to estimate water demand. Such information is critical to water resource managers in their assessment of the effectiveness of their decisions. Heines and Luckey (1980) evaluated the use of Landsat multispectral data in combination with water use according to crop to estimate groundwater demand in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. The results provide general information on water use by the region, but the scale of application of this particular project made it difficult for scientists to assess the accuracy of the estimation.

Similar types of data on irrigated crop acreages have been combined with water-use rates in areas outside the High Plains region to estimate evapotranspiration (Raymond and Owen-Joyce 1986). Within the High Plains region Walsh (1986) investigated the relationship between the crop-moisture index, a meteorologically based drought index, and the characteristics of vegetation assessed through remotely sensed data sampled during a growing season in Oklahoma. He derived remotely sensed data using a one-kilometer resolution Advanced Very High Resolution Radiometer of the NOAA satellite. The method provided insight for water planners relative to demands on the groundwater resources during periods of high drought.

Still other research offers a three-step approach for understanding more aspects of the groundwater management system in the High Plains. With such an approach, remote sensing data is classified into categories of irrigated and nonirrigated land cover. The data are then integrated with a water-use rate according to the land cover. The third step combines this information with topographical data to predict another aspect of the water management system. A study by Astroth, Trujillo, and Johnson (1990) provided a procedure for combining remote sensing with geographic information systems to determine energy-related factors of the groundwater management system in Oregon. In the High Plains, where pumping costs for irrigation continue to increase, such an approach promises insights into methods for the prediction of energy requirements for particular areas of irrigation and their potential for development.
WESTERN KANSAS CASE STUDY

The need for accurate statistics on water demand in the limited groundwater resource areas of the Kansas High Plains has led to increased interest by the state of Kansas in exploring methods other than flow meters for estimating this demand. The political and economic constraints associated with meters necessitate alternatives. The cost of a meter (excluding labor) on a new well in northwest Kansas is approximately $400. Retrofitting existing irrigation wells with meters would cost $500 to $3,000, depending on the pipe configuration at the well. Since a large majority of the wells would require retrofitting, the cost of installing meters on wells throughout northwest Kansas alone would be approximately $1.8 million, excluding maintenance and monitoring costs. The meters generally have a life expectancy of seven to ten years (Bossert 1987).

To provide accurate information on water demand at a low cost in the Kansas High Plains, the U.S. Department of Interior and the Kansas Water Resources Research Institute funded a project, completed in 1987, to determine the potential for using remote sensing in combination with other information for estimating water demand in Northwest Kansas Groundwater Management District No. 4. The district has required meters on all new irrigation wells since May 1981 and thus can serve as a case study, providing critical data on irrigation pumping rates and water demand that can be used in developing a model.

The spatial model required input on the crop area derived from remote sensing and field transects, including method of irrigation, crop water requirements, metered water-use rates, and precipitation (Figure 7.2). The irrigated crop area was determined using Landsat multispectral scanner data acquired for different dates during the growing season. Dates in late April, early May, late July, early to mid-August, and early September were required to provide crop response for the range of cropping calendars associated with crop types in the district and to avoid cloud cover during some stages of the satellite overpass. Landsat digital data were converted into major categories of irrigated crop type, using multiband ratioing of bands 4 and 2 and a maximum likelihood classification procedure (Table 7.2). Data also included a classified irrigated crop area, using the maximum likelihood classification procedure.

The maximum likelihood approach applies two weighted factors to a probability estimate. First, the analyst determines the anticipated likelihood of an occurrence for each class in the scene. For example, when classifying a pixel or a digital value for the image, the probability of irrigated corn may be weighted more heavily than a less likely crop.
Second, the weight or "cost" of misclassification is applied to each class. These two factors act to minimize misclassifications (Lillesand and Kiefer 1987).

Because of the annual variation in growing-season precipitation (April-October), the amount of water required for irrigated crop production varies. Therefore, the irrigation coefficients by crop type and the irrigation method as determined by the U.S. Department of Agriculture were modified by a precipitation coefficient, which reflects the deviation of precipitation from a normal distribution. Baker demonstrated the approach (1983) by correlating precipitation amounts during the crop-growing season with crop water requirements and by using the resulting data to estimate rates of groundwater withdrawal in southwest Kansas. The precipitation in 1986 was less than 1 percent (0.9) above the norm and is reflected in the irrigation requirements by crop (see Table 7.2).

When one compares the predicted value using the remote sensing model with metered well data, the accuracy for the model is approximately 96 percent. The annual costs associated with such an approach are less than $20,000 for an area the size of northwest Kansas, a significant savings over retrofitting for metered wells.
Table 7.2. Remote Sensing Derived Irrigated Land Cover Data and Irrigation Requirements, 1986 Irrigation Season, Northwest Kansas (in acre-feet/acre)

<table>
<thead>
<tr>
<th>Crop Type</th>
<th>Acres</th>
<th>Irrigation Requirement</th>
<th>Water Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfalfa</td>
<td>53,400.6</td>
<td>2.01</td>
<td>107,335.21</td>
</tr>
<tr>
<td>Corn</td>
<td>163,946.2</td>
<td>1.27</td>
<td>208,211.67</td>
</tr>
<tr>
<td>Sorghum</td>
<td>69,839.0</td>
<td>1.08</td>
<td>75,426.12</td>
</tr>
<tr>
<td>Soybeans</td>
<td>28,323.9</td>
<td>1.04</td>
<td>29,456.86</td>
</tr>
<tr>
<td>Sunflowers</td>
<td>46,575.1</td>
<td>1.05</td>
<td>48,903.86</td>
</tr>
<tr>
<td>Wheat</td>
<td>69,946.8</td>
<td>0.93</td>
<td>65,050.52</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>534,384.24</td>
</tr>
</tbody>
</table>


USING REMOTE AND GEOGRAPHIC INFORMATION SYSTEMS FOR MONITORING GROUNDWATER QUALITY

Scientists have used the techniques of remote sensing and geographic-information systems for monitoring groundwater quality in the High Plains region (Ripple and Miller 1982; Pritchard 1987-1988). In spring 1979, the South Dakota Department of Water and Natural Resources initiated a project with the aid of the state Planning Bureau for water-quality planning. Using color infrared aerial photography and Landsat imagery, planners developed maps of potential groundwater pollution based on information concerning land cover, soil permeability, location of the water table, and slope gradient. This approach alleviates the problems of obtaining current, comprehensive land-use/land-cover data and combines information effectively. By using a storage and retrieval system of georeferenced computer-data information, the planners gained many options. This particular case study demonstrates the potential savings in applying this approach to more extensive areas of the High Plains region.

In a more recent effort, the Center for Advanced Land Management Information Technologies (CALMIT) has utilized a remote sensing/geographic information system for mapping areas of an aquifer's vulnerability as part of the Nebraska Department of Environmental Control's effort to designate special groundwater protection areas (Pritchard 1987-1988). The system, called "DRASTIC," combines information on hydrogeology and soils into one map that shows the vulnerability of the aquifer to pollution in a specific region (Figure 7.3). DRASTIC is the acronym for the seven mappable factors:
Landsat maximum likelihood classification of an area of irrigated cropland in northwest Kansas.

D = Depth to water  
R = Recharge  
A = Aquifer media  
S = Soil media  
T = Topography  
I = Impact of the unsaturated zone  
C = Hydraulic conductivity

Developed in 1985 by the National Water Well Association and the U.S. Environmental Protection Agency, DRASTIC was first used as a joint project by CALMIT and the Nebraska Department of Health to evaluate the potential for groundwater pollution at Cozad, Nebraska. The Nebraska Department of Environmental Control became interested in the technology as a means of determining special protection areas after the passage in 1986 of the Nebraska Groundwater Management and Protection Act. The act was the legislative response to increasing groundwater contamination by nitrates and other nonpoint source pollutants. Before a special protection area can be designated, however, a detailed study of the area must be conducted. DRASTIC allows a standardized approach for determining the vulnerability of groundwater.
Each factor of DRASTIC is given a rating of 1 to 10, with 10 as most vulnerable and 1 as least vulnerable. The rating scale is weighted relative to the seven factors present in a specific area. Depth to water, for example, is one of the more important factors in determining pollution potential. A range of 0 to 5 feet in depth to water is rated at 10; 100 feet or more is rated at 1. Topography or the slope of the land surface affects how quickly a contaminant penetrates the soil; a flatter surface allows a contaminant to infiltrate the soil more rapidly. 0 to 2 percent slope, for example, is rated at 10; an 18-plus percent slope is rated at 1. The computer combines the data onto a single map that shows the aquifer's vulnerability.

As decisions about water resources grow more critical in the High Plains region, the need for more data and for improved methods of storage and retrieval increases correspondingly. Thus remote sensing technology and geographic information systems are serving as valuable tools for the High Plains water resource manager. With the improvement in resolution of sensors and in analysis, remote sensing will play an ever more important role in providing information about irrigated areas, cropland changes and conditions, water needs, uniformity of water distribution in irrigated fields, and variations in water demand and in pollution of groundwater resources.

Software and hardware for remote sensing and geographic information systems continue to decrease in cost. Computer-compatible
data bases (e.g., soils, topography, and land) are increasingly available from state and regional organizations at low cost; microcomputer technology has moved to the county and to the offices of regional water management. Water managers are limited only if they are uncomfortable with user-friendly software packages.

Remote sensing and geographic information systems can provide water-resource data on a variety of levels. On a small scale, data focusing on irrigated acreage and water demand are important to the regional, state, and federal decision makers; on a large scale, data centering on crop stress associated with irrigation and water quality are more useful to the individual operators. Remote sensing and geographic information systems have grown ever more sophisticated since the late 1980s, particularly the two- and three-dimensional models, and can be processed on microbased computer systems at all levels of the water management system. As these technologies continue to improve, so too will the potential for groundwater monitoring.

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