CHAPTER 59

GIS in Precision Agriculture and Watershed Management

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59.1 Introduction

The technologies used to support the agriculture industry have changed significantly in the last 20 years. While genetic plant and animal research have improved varieties and yields, the introduction of information systems and precision management techniques have allowed reduced inputs, including nutrients, herbicides, and pesticides, increased yields, and reduced environmental pollution, particularly at the field and watershed scales. The technologies that have provided a base in these improvements in agricultural production and watershed protection include the Global Positioning System (GPS), remote sensing, geographic information systems (GIS), and variable rate technology (VRT) equipment. It is the purpose of this chapter to document the basis of these technologies and their use in precision agriculture and watershed management. The chapter is organized to present the basic technologies and methods used in precision agriculture and watershed management followed by the actual description and application of these technologies to these areas. We present the cartographic basis, followed by a description of remote sensing in agriculture, and provide some basic GIS operations critical to the application areas. We then describe precision agriculture, soil mapping, and watershed management and modeling.

59.2 Cartographic Basis

The rectification of geospatial agricultural data, including images, sample locations, interpolated surfaces, yield, and other data, require specification and transformations of spheroids, datums, map projection, and coordinate systems. A spheroid is the reference ellipsoid for the figure of the Earth. A particular coordinate system is constructed based on a specific reference spheroid, datum, and map projection.

59.2.1 Datums and Coordinate Systems

A datum is the basis of a coordinate system, including a spheroid of reference, an initial point, and a reference angle (not required for geocentric systems). Common datums used in precision agriculture and watershed modeling include the North American Datum of 1927 (NAD 27). This datum is the basis of most US maps constructed prior to 1980. The North American Datum 1983 (NAD 83) is also used extensively. It was developed with satellite positioning technology. For agricultural applications the World Geodetic System 1984 (WGS 84) datum using the WGS 84 spheroid is essentially identical to NAD 83 and is the basis of coordinates obtained with GPS. Between NAD 27 coordinates and NAD 83 coordinates, positional differences can be 200 m in plane-projected space in the continental US (Welch and Homsey 1997).

A map projection is a systematic transformation of spherical coordinates, latitude (φ) and longitude (λ), to a plane coordinate representation. For a detailed treatment of map projections see Snyder (1987) and Usery et al. (2008, Chapter 8, this volume). Common projections used in precision agriculture and watershed management are the transverse

Mercator and the Lambert conformal conic, which are the basis of the Universal Transverse Mercator (UTM) and state plane coordinate (SPC) systems, the preferred coordinate systems for large-scale (small areal extent) applications.

In the UTM system, the *x* coordinates are referred to as Eastings and the *y* coordinates as Northings. The system is projected from the spheroid in 6 degree zones on the transverse Mercator projection for areas 80 degrees south to 84 degrees north. The 6-degree wide projection zones achieve an accuracy of 1 part in 2,500 or a scale factor (SF) = 0.9996. The UTM coordinates are a worldwide system with units in meters. The central meridian of each zone, or normally the $x = 0$ m coordinate value, is offset to a value of 500,000 m to insure positive coordinate values throughout the zone.

The SPC system also uses Eastings and Northings. It is constructed by state with zones that are 158 miles or less in width. Similar to UTM zones, each SPC zone is independently projected, but the projection in use depends on the orientation of the long axis of the state (and zone). The transverse Mercator projection is used for north-south trending states such as Georgia or Illinois; the Lambert conformal conic projection is used for east-west trending states and zones such as Tennessee and North Carolina. States including Florida, New York and Alaska use both projections. The projection of a zone of 158 miles or less allows achievement of an accuracy of 1 part in 10,000 or an SF = 0.9999. The SPC system exists only in the US and uses official units of the US foot if developed from the NAD 27 datum and meters for NAD 83.

59.2.2 Global Positioning System (GPS) and Differential GPS

Accurate positioning is very important to agricultural managers, watershed modelers, and farmers employing precision techniques. Collectively, they need answers to the fundamental question of where on the Earth we are. From the launch of Sputnik in 1957, scientists and engineers have been using transmitted radio frequency signals from satellites to make range, or distance, observations. Today, satellites employing ranging procedures like those in the Global Positioning System (GPS) can routinely provide us with an accurate position on the Earth's surface to better than 10 m in absolute measures and 10 cm when relative techniques are used (Wells et al. 1986). These accomplishments have their roots dating to the early eighteenth century when Edmund Haley calculated the orbits of comets using Sir Isaac Newton's techniques. Haley predicted the return of a comet observed twice before in history (Armitage 1966).

The Swiss mathematician Leonard Euler followed Haley's accomplishment when he derived the first completely analytical method for solving a parabolic orbit (Bate et al. 1971). From Euler's era forward, we have used time and orbit determination as fundamental parameters of position. Employing these positioning methods, we now use techniques developed by the great mathematician Karl Friedrich Gauss. Namely, we minimize the errors inherent in observations of orbits to reach the greatest precision attainable in determining a position (or orbit) by accumulating the greatest number of perfect observations and adjusting them to agree with all observations in the best possible manner (Gauss 1857; O'Neil 1987). Further detail on point positioning can be found in Torge (1980) and in Vanicek and Krakiwsky (1986).

The Navigation Satellite Time and Ranging (NAVSTAR) GPS consists of satellites, the control system, and users. The US Department of Defense began work on NAVSTAR/GPS in 1973 and designed the array of satellites in six orbital planes inclined 55 degrees to the Earth's equator (Figure 59-1) (Wells et al. 1986). They orbit the Earth at 20,000 km and continuously transmit radio pulses at known times.

The radio ranging designed into the GPS uses a primary signal at 1575.42 MHz and a secondary signal at 1227.6 MHz. The primary, or *L*1, frequency has two modulations: the C/A-code and the P-code (Parkinson 1996). The C/A or Clear Acquisition code is a short pseudorandom noise code broadcast at a bit rate of 1.023 MHz. The P or Precision code is a

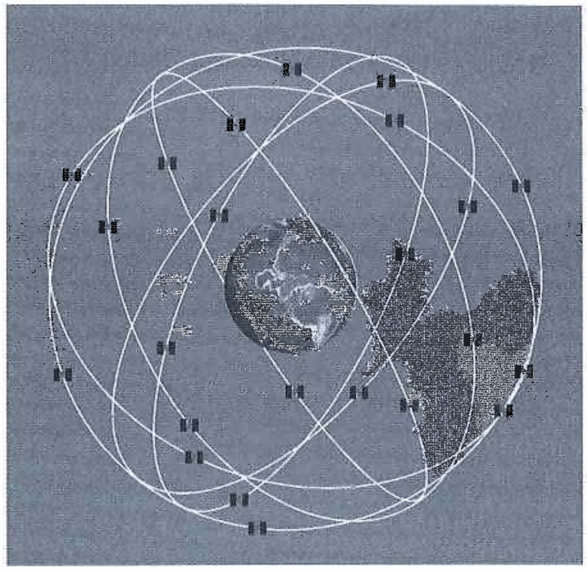

Figure 59-1 GPS satellite array (from NASA 2008).

very long code that is broadcast at 10.23 MHz (Wells et al. 1986; Van Dierendonck 1996). A third modulation of the carrier signal is the broadcast message or data modulation. This is used as a communication link through which the satellite transmits its location and corrections to the on-board atomic clock (Parkinson 1996). The control component consists of five stations around the planet, which track the satellites. A further four stations monitor the orbits, and the master control in Colorado Springs, Colorado, USA, corrects the navigational messages received from the satellites.

Receiving equipment measures the instant when pulses arrive to determine distances to the satellites. This distance determination is called radio ranging. It is a subcategory of general ranging techniques and is similar to triangulation in surveying. By measuring the precise time a signal is received from a known satellite, we have a value for the range vector, $\mathbf{r}_{ij}$ (Figure 59-2). Because we know precisely the position of the satellite that emitted the signal from its ephemeris, we know the satellite position vector, $\mathbf{r}_j$ (from the center of mass of the Earth). Thus, we can calculate the position vector of the receiver (antenna), $\mathbf{r}_i$ from the following equation:

$$\mathbf{r}_{ij} = \mathbf{r}_j - \mathbf{r}_i \tag{59-1}$$

Substituting the vector components, we have:

$$(X, Y, Z)_{ij} = (X, Y, Z)_j - (X, Y, Z)_i \tag{59-2}$$

This leads to the basic math model for ranging as follows:

$$F_{ij} = [(X_j - X_i)^2 + (Y_j - Y_i)^2 + (Z_j - Z_i)^2]^{0.5} - \mathbf{r}_{ij} = 0 \tag{59-3}$$

If $\mathbf{r}_i$ is stationary, then at least three non-coplanar ranges must be measured. This allows us to solve a series of equations for the three unknown components of $\mathbf{r}_i$ (Wells et al. 1986). Using algebraic equations, clock errors from both the satellites and the receiver are determined and adjusted to provide an exact location for the receiver (Herring 1996).

The system was originally designed for military and navigation uses and was quickly adopted for use with large survey control projects. Since the 1980s, when the GPS' most accurate timing was made available to civilian uses in addition to military uses, numerous practical applications of GPS have grown to fruition in addition to precision farming and

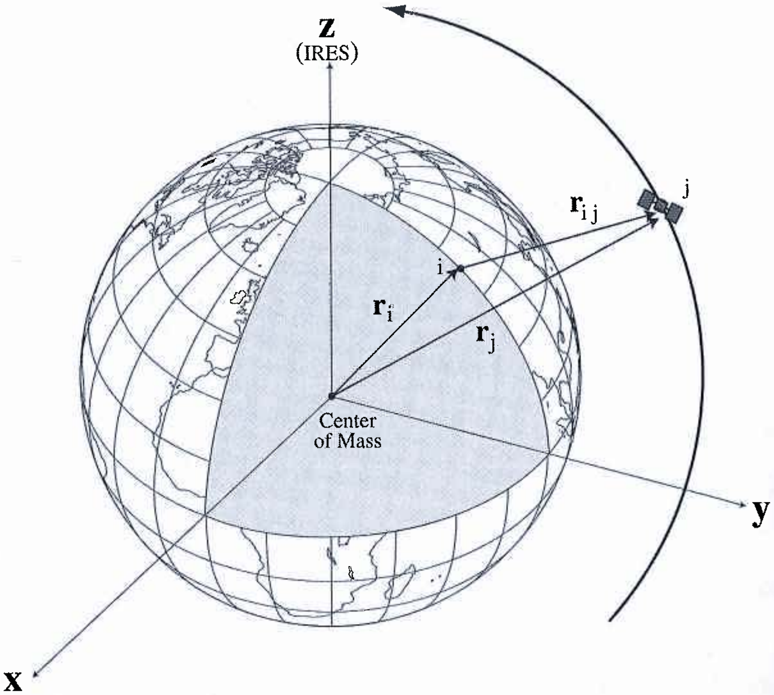

Figure 59-2 Schematic of basic terrestrial point positioning using satellite radio ranging.

watershed modeling, such as automobile navigation, geo-caching, and recreational fishing (Garmin 2000). The current GPS is composed of second-generation satellites, called Block II, which became fully operational in 1995, and is currently undergoing modernization through the GPS IIR-M series. There are currently 29 GPS satellites in orbit and each takes about 12 hours to orbit the Earth once (Grisso et. al. 2003; SpaceDaily 2006).

The GPS is a crucial technology in precision agriculture that allows farmers to obtain data of within-field unevenness of a variety of limiting factors such as soil acidity and crop yields (Goering 1993; Usery et al. 1995). Precision farming techniques can enhance production and diminish environmental pollution by reducing the amount of chemicals spread over a field. For example, recording the yield variability permits a farmer to explore, at a specific location within the field, the extremely low-yielding or extremely high-yielding areas (Auernhammer et al. 1994; Usery et al. 1995).

Differential GPS (DGPS) works by having a reference station with a known location and a mobile GPS receiver. The reference station determines the errors in the satellite signals by measuring the ranges to each satellite using the received signals and then compares these ranges to the calculated ranges from its known (or true) location. The difference between these two ranges becomes the differential correction. For instance, to improve the accuracy of location of a GPS receiver on a tractor or harvester, the unit on the tractor applies these differential corrections to calculate the tractor's location more exactly (Figure 59-3). In the case of a roving receiver, carried by a person or mounted on a harvester, the receiver unit applies the correction by decoding the error code transmitted by the reference station. The reference station's signal includes the timing errors for each satellite and an additional "rate of change error" for them. Then the roving receiver interpolates its position precisely (Garmin 2000; Trimble 2006). Computer hardware and GIS software, used for incorporating geospatial data analyses and management, are critical components to couple with DGPS technology in order to maximize the results desired in modeling and farming.

However, not everything is perfect in this world of DGPS. Users should be aware that degraded positioning accuracies might occur when magnetic storms cause loss of signal lock

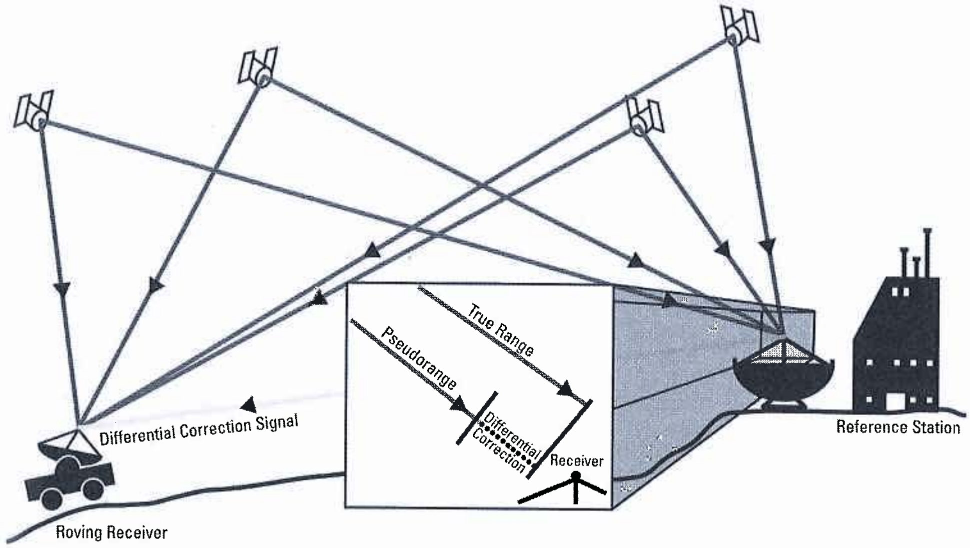

Figure 59-3 Example of applying a "differential correction" to a GPS receiver. See included DVD for color version.

(Skone 2001). In addition, because the reference station compensated errors vary with space, users can suffer accuracy degradation as the distance between their mobile receiver and the reference station increases. This distance factor is the most important factor determining DGPS accuracy and it is further exacerbated by a lack of inter-visibility, the inability of the reference and user to see the same satellites (Monteiro et al. 2005). Fortunately, in the US, on a daily basis, positional coordinates are computed for a network of ground-based GPS stations that comprise the National Continuously Operating Reference Stations (CORS). The US National Geodetic Survey provides this monitoring service to update coordinates and velocities of CORS sites. This update accounts for changes of antennae positions caused by human effects or natural effects, such as tectonic plate rotations, and is critical to rigorous DGPS positioning (Soler et al. 2003)

Although degraded positioning accuracies can occur, it is important to realize that the improved positional accuracy of a GPS receiver mounted on a tractor using DGPS can provide a location within centimeters (Wells et al. 1986). Thus, there are many uses of GPS point positioning that ultimately allow environmental scientists and agricultural managers, who rely greatly on exact positions, to answer to the fundamental questions of where am I now, or where do I need to apply pesticide. Knowing the specific location of variables, such as crop types, temperature, precipitation, slope, and soils, among others, and using this information in conjunction with DGPS, remote sensing, GIS, VRT and related technologies, farmers can increase profits through selective application of fertilizers, and land stewards can reduce risks by minimizing exposure of pesticides, herbicides, plant nutrients, and other chemicals to the ecosystem.

59.2.3 Scale

Scale can be defined in many ways. For example, *The Merriam-Webster Online Dictionary* (http://www.m-w.com/) contains seven primary definitions of scale; four as nouns and three as verbs. The noun definitions form into two classes: one dealing with weights and measures, and the other dealing with coverings on animals and plants (e.g., fish scales). For GIS and GIScience the definition of interest is the one dealing primarily with measurement. From engineering, surveying, and cartography we refer to scale as being a representative fraction (RF) of something portrayed schematically in ratio to its true size, as follows:

$$RF= (\text{portrayed size/actual size}). \tag{59-4}$$

Scale is expressed in mapping and cartography as the ratio of a map distance to the distance on the Earth (with the distance on the map being expressed in unity). According to Robinson et al. (1995), scale can be stated verbally, graphically, or most commonly, via the RF, such as 1/500,000 or 1:500,000. They note that scale can be elusive because map scale varies as an inherent effect of the spherical or ellipsoidal dimensional transformation associated with map projections (see Usery et al. 2008, Chapter 8, this volume). Despite this elusiveness, cartographic scale is generally considered an absolute scale.

An RF of 1:500,000 indicates that one unit of linear horizontal distance on a map corresponds to 500,000 of the same units on the ground. Star and Estes (1990) give a nice mnemonic on the terms small scale and large scale, stating that an object on a small-scale map (e.g., 1:2,500,000) appears smaller than the same object on a large-scale map (e.g., 1:5,000).

In ecological and landscape studies, including agricultural and watershed management applications, alternative definitions are often used—such as field scale, basin scale, or watershed scale to continental and global scales. Spatial scale is essential to the understanding of natural and anthropogenic-influenced ecosystems. Often, terms of scale used in these disciplines become ones of relative scale or geographical extent. Lam et al. (2004) use scale with four meanings or types, measurement (resolution, grain), operational, observational (geographic/extent) and cartographic (representation). All of these meanings are used in agriculture and watershed management.

The problems with relative scale definitions are twofold. First, when they are used with terms such as small scale (small geographic area) and large scale (large geographic area), they are usually used in opposition to how they are used with the absolute scale meaning. For example, often the term field scale is used interchangeably to mean small scale and basin scale is used to mean large scale. This relative term for small scale (field scale) is opposite to what the absolute term means for small scale. In terms of absolute scale, a field would be considered large scale (large detail—as depicted on a 1:4,800-scale topographic map). Likewise, a large-scale (basin scale—say the lower Mississippi) relative term would be considered a small (or intermediate) scale in absolute terms (at a 1:500,000-scale topographic map, for example).

The second problem with the relative scale terms used this way is that there are no standard definitions. What does field scale mean quantitatively? How about basin scale? We know that a watershed or drainage basin is a finite area. The basin holds a network of channels (often with a unique pattern) that drain it, and it is separated from other basins by a divide (Ritter 1986). That which differentiates a basin or a sub-basin in the spatial domain is arbitrary. Due to oversimplifications of complex physical processes in the merging of digital spatial data for representations of phenomena such as soils, precipitation, and temperature—and the models that use them as input—issues of scale become of paramount importance to precision farming and watershed modeling (Goodrich and Woolhiser 1991; Song and James 1992). Singh (1995) defines the importance of scale to modeling as the size of a subwatershed within which the hydrologic response can be treated as homogeneous. Therefore, the optimal scale in a watershed is determined by the collective workings of multiple processes that generate hydrologic response and the availability of hydrologic data.

For the United States, the Hydrologic Units Codes (HUCs) used by the USGS allows us to impose some hierarchy into the relative scale problem in watershed management. Hydrologic Units are nested, from the smallest cataloging units, to accounting units, to subregions, to the largest regions. Nationally, there are 21 regions that contain either the drainage area of a major river or the combined drainage areas of a series of rivers (Seaber et al. 1987). Each of the four levels of hierarchy contains a 2-digit code. So a 2-digit HUC represents a region and an 8-digit HUC represents a cataloging unit. The cataloging units are often referred to as a watershed. The HUC coding system still leaves a relative scale problem but the hierarchy allows us some control and common understanding of scale. Currently, for the 48 contiguous states, there are 18 regions, 204 subregions, 324 accounting units, and 2,111 cataloging units (USGS 2006).

In watershed management and precision farming applications, moving between these relative scales on which a GIS practitioner can operate changes the discernible detail available for analyses. For example, Meentemeyer and Box (1987) note that scale changes may dramatically change watershed model structures because some variables change more significantly than others with a change in spatial scale. Further, they note that an increase in the size of a study area tends to increase the range of values for a landscape variable.

Scale issues are directly related to resolution issues, with which GIS practitioners and scientists deal routinely. Raster data sets are used repeatedly in precision farming and watershed modeling applications. These data sets are often derived from satellite observations or some gridded natural phenomena such as temperature or land cover. There are inherent scale-related errors in the creation of these types of data and any subsequent aggregations of them, collectively known as raster or grid resolution, or simply resolution (Usery et al. 2004). Resolution issues and errors are extremely important to all environmental modelers, not just watershed modelers, because, as Willmott and Johnson (2005) point out, many physical phenomena are highly variable over space and much of the phenomenon's spatial variability can be lost when the resolution is too low.

Ultimately, we can define scale in many ways. GIS practitioners concerning themselves with watershed management or precision farming need to be aware of the variety of definitions and uses of scale-related terms in this arena. If possible, an absolute measure of scale such as the RF is preferred. Perhaps a better way to deal with the various uses of terms like small scale and large scale among an interdisciplinary group of scientists and technicians is to use the terms broad scale or coarse scale on one end of the spectrum and narrow scale or fine scale at the other end.

59.3 Remote Sensing for Agriculture

Remote sensing is the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation (Lillesand et al. 2008). As you read these words, you are employing remote sensing. Your eyes are sensors and they respond to light reflected from this paper. Through the use of sensors, we collect data and analyze the data to produce information. With remote sensing, the data are signals from the electromagnetic spectrum. While the electromagnetic spectrum spans cosmic rays to radio waves, remote sensing commonly uses only specific portions of this spectrum. The visible spectrum from approximately 400 to 700 nm in wavelength, and the wavelengths to which our eyes are sensitive, is commonly used in remote sensing, but we extend the spectrum to include the infrared wavelengths in the range of 700 to 1,100 nm and refer to it as the photographic spectrum. Also, active sensors including longer wavelength radar and, recently, visible wavelength lidar are used for vegetation and canopy structure. We usually sense a range of wavelengths in remote sensing with each range referred to as a band. For the photographic spectrum, common bands are approximately 400 to 500 nm (blue), 500 to 600 nm (green), and 600 to 700 nm (red), and 700 to 1,100 nm (infrared) bands. While these wavelength ranges have been traditionally used for remote sensing of Earth phenomena, the introduction of hyperspectral sensors, i.e., sensors that detect narrow wavelength bands of 10 nm or so with hundreds of bands, has extended the use of remote sensing in agriculture and in many other areas. Also in recent years radar in the C, X, and L bands have been used for vegetation applications (Jensen et al. 2004).

A full literature of the theory and practice of remote sensing has been developed (Colwell 1983; Lillesand et al. 2004; Jensen 2005) and thus will not be replicated here. This section will focus specifically on the use of remote sensing, and particularly remotely sensed images, for agricultural applications. Agricultural phenomena commonly detected and recognized in remotely sensed images include vegetation types, vegetation health, biomass, soil types, soil moisture, and crop yield. Additional vegetation characteristics detectable and measurable include stress, moisture content, landscape ecology metrics, surface roughness, and canopy structure (Carter 1993; Carter et al. 1996; Frohn 1998; Jensen et al. 2004).

59.3.1 Basic Concept of Remote Sensing

The basic concept on which all remote sensing relies is that Earth objects reflect various wavelengths of light in differing amounts. We can identify reflectances of specific wavelength ranges for specific objects to develop a ***spectral signature.*** The spectral signature can be used to identify the Earth object in composite remotely sensed images or images with multiple wavelength bands. For agriculture, we commonly use this concept to identify vegetation types, such as crops versus forest or individual species of crops, grasses, and rangeland. The processing approaches to identify these crops include unsupervised and supervised classification (Lillesand et al. 2004; Jensen 2005), neural networks, and recently knowledge-based and learning classifiers using computer approaches, such as Holland classifiers, and genetic algorithms (Bandyopadhyay and Pal 2001; Liu et al. 2004; Yang and Yang 2004). The results of these classifications include not only species types, but also moisture content, stress levels, organic matter content, clay content, and many other characteristics of plants and soils that are useful for agricultural management.

A variety of processing techniques of remotely sensed images is required to make them useful for agricultural or watershed management. Some of these methods include geometric and radiometric correction, image enhancement, feature extraction, and mapping. Specific techniques with particular applications in agriculture include indices computed by image band combinations, band ratios, and image transformations resulting in measures of plant characteristics such as biomass, chlorophyll and moisture content. Some of these methods include the Vegetation Index (VI), the Normalized Difference Vegetation Index (NDVI), and the Kauth-Thomas or Tasseled Cap transformation, which yields images of brightness, greenness, and wetness (Figure 59-4). These and other methods are documented in Jensen (2007) and available in standard remote sensing software packages such as ERDAS Imagine (Leica Geosystems 2006) and ENVI (RSI 2006).

For remote sensing of agricultural information, spatial resolution determines the application and accuracy. Low resolution, for example 1 km as with Advanced Very High Resolution Radiometer (AVHRR) images, implies broad area analysis. Applications include determining land cover, crop inventory, and weather patterns. A good example of this is the use of NDVI generated from AVHRR to show the greening of America over the early spring and summer (KARS 2005). Field-specific applications require high resolution data, such as the width of a harvester—1 to 10 m. For weed and insect detection, the spacing determines the resolution requirements, commonly in the range of 1 to 3 m.

Other agricultural applications include detection and measurement of soil properties and soil inventory (Johannsen et al. 2006). Soil properties affect the reflectance in an image based on the influence of soil conditions on response. Such reflectance changes allow mapping soil patterns, moisture, organic content, clay and other mineral components and other characteristics.

The spectral reflectance in remotely sensed images is a product of vegetation response, which can be used to define soil management zones. Once management zones are defined they can be sampled as separate units and nutrient applications can be adjusted as needed (SSMG-22).

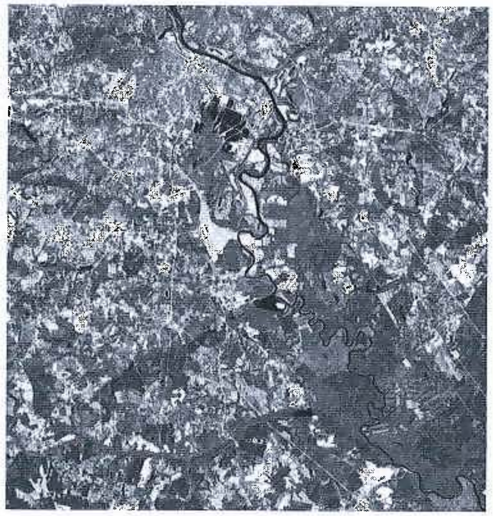

Figure 59-4a Brightness image of Augusta, Georgia, area, extracted from an Enhanced Thematic Mapper Plus (ETM+) image.

Figure 59-4b Greenness image of Augusta, Georgia, area, extracted from ETM+ image.

Figure 59-4c Wetness image of Augusta, Georgia, area, extracted from an ETM+ image.

For crop inventory and yield prediction, remotely sensed images can be used for crop identification, inventory of areas planted, estimation of potential harvest, and yield prediction based on NDVI. Commercial programs and government authorities are using remote sensing for monitoring production and compliance with regulations (CROPINS 2006; USDA 2006).

Soil nutrient detection from images is based on pixel reflectances that result from soil characteristics (e.g., color) that are related to organic content. From organic content one can predict nitrogen (N) release to plants. Leaf greenness related to chlorophyll content, which directly relates to N, can also be detected. Discoloration may be a result of potassium (K) deficiency. While possible, particularly with newer hyperspectral images and methods, other chemicals are usually difficult to detect from image data.

Detection of vegetation change is a major application of remotely sensed images. For example, green and infrared bands highlight volume of vegetation (biomass) and indicate plant vigor. These bands can be used to create crop vigor maps and change detection in the vitality of plants. Images can also be used to determine crop injury, for example, from hail and wind damage. An example is a project to determine damage to corn in Indiana from a tornado. The project used before and after images, and the corn downed from winds was detectable.

Images can be used for crop residue evaluation, such as determining the Farm Service Administration's (FSA) erodibility values that require minimum levels of crop residue to reduce wind and water erosion. Remote sensing is a good method for managing the supervision of standards. For example, Landsat Thematic Mapper (TM) images can be used to distinguish different types of crop residue.

Detecting crop stress from drought, weed, insects, erosion, and nutrient deficiency is a significant application of remote sensing to agriculture. These types of problems all result in stress that is detectable through vegetation indices, such as the brightness, greenness, and wetness images from a Tasseled Cap transformation. Change detection, based on before and after stress conditions, can be used to help manage crop vigor and growth.

A standard result from remote sensing is determination of land cover. While land use usually cannot be determined, the land cover can, with categories dependent on spectral and spatial resolution. Land cover maps from remotely sensed images are used by the USDA to assess regulation compliance, among other applications.

59.4 GIS Databases, Manipulation, and Processing

59.4.1 Building a GIS Database for Precision Farming—A Generalized Approach

Building a database for precision agriculture and watershed management requires specific data for the type of management application to be implemented. However, there is a set of common data and procedures that establish the basic GIS framework and allow manipulation and processing of the data to support the management application. These common data sets and a procedural framework for building a GIS database follow.

59.4.1.1 Data Acquisition

1) Determine the coordinate system to be used for the GIS database. Account for spheroid, datum, projection, and coordinates (see Chapter 8, Section 3, this volume). Good choices are the State Plane and UTM coordinates, for which the listed parameters are standard and accuracies are defined.
2) Establish high-accuracy base information.

A) Acquire high-accuracy (0.1 m root-mean-square error [RMSE] or better) ground control points (GCPs) over the field for which the database is to be constructed. Ideally, GPS equipment will be used on targeted points, which will appear in high-resolution photos acquired over the field. A minimum of 15 to 20 points are usually needed depending on field size.

B) Acquire high-resolution, high-quality base image data. At a minimum, one of the following is necessary:

i) High-resolution photograph (nominal scale of 1:5,000 or better) or digital image (0.1 to 1 m pixel digital equivalent resolution) over the field under bare soil conditions with targeted GCPs. This is the preferred base data.

ii) Existing US Geological Survey digital orthophotographs of 1 m resolution.

C) Digital elevation data with 1 m or better post spacing of elevation values and vertical accuracy of 0.l to 0.5 RMSE.

3) Acquire field data.

A) Acquire any existing soils maps from USDA, etc.

B) Acquire soil samples on a grid spacing of one acre or better with GPS coordinates in the chosen system. A fine grid sample or field stratified samples are the best choices.

C) Acquire field history information on a variable within field basis or summaries for entire field if no variable data exist. Assimilate all information known to be available. Examples include:

i) Crop production histories including types of crops, yields, rotation cycles, etc.

ii) Yield data.

iii) Tillage history.

iv) Field maps of compacted areas, terracing, and others.

v) Field input maps or histories (fertilizers, lime, herbicides, pesticides, and others).

vi) All other data available.

4) Acquire additional data to suit applications of database. These may include:

A) Electromagnetic induction images.

B) Vegetation index maps.

C) Others.

5) Acquire data throughout the growing season and at harvest time as variable maps, if applied that way:

A) Periodic aerial images (color infrared).

B) Input applications (nutrient, herbicide, pesticide, and others).

C) Scouting reports.

D) Yield data.

59.4.1.2 Data Processing

1) Convert all map and image data to the selected coordinate system.

A) For base photo (bare soil image), rectify using GCPs. If the field is reasonably flat, this simple process will be sufficient. However, for a field with considerable relief (20 m or more) use of a high-resolution DEM in a differential rectification process may be needed. This may require contracting a GIS or photogrammetric consulting service to use the DEM to create the orthophotos since most GIS only support simple rectification with GCPs as we performed in the laboratory exercises.

B) Transform all other data layers to match the base image using the GCPs with standard rectification methods (see Chapter 8, Section 3, this volume).

2) Interpolate point data sets (e.g., soil samples) to a raster grid and match the cell size to base data or desired resolution.

3) Convert scouting data or other samples to polygon or raster map formats.

4) Convert vector data to raster form as needed to match processing and modeling needs.

5) Build models from data as required to support applications.
   A) Models should be built conceptually in graphic or diagrammatic form prior to any attempts to use data layers in models.
6) Implement models to determine desired results.

59.4.1.3 Building a GIS Database for Watershed Modeling

Follow similar procedures for precision farming beginning with the control and base information. Layers will vary but will typically include:

1) Base image (orthophoto) and map (Digital Raster Graphic of topographic map).
2) Digital elevation data.
3) Land cover at appropriate resolution and classification system for size and application of study area.
4) Soils data from NRCS Soil Surveys.
5) Precipitation data.
6) Other data as required for specific application. For example, for watershed analysis, point samples of water flow and water quality are usually needed.

59.4.2 Data Manipulation and Processing

While there are many GIS processing operations that are necessary for precision agriculture and watershed management, several specific operations including spatial interpolation and modeling are particularly important and are discussed briefly below. The description in this section is to demonstrate the application of these operations to specific agriculture and watershed data sets.

59.4.2.1 Spatial Interpolation

Sampling for soil chemicals, nutrient content, and organic matter is invariably performed with point locations, often in a gridded pattern, but also along soil management zones or as stratified random samples (Pocknee 2000). Elevation data are commonly generated as samples from images or other sources and yield data results in a dense set of posting points with a yield value at each location. To be useful in a GIS analysis context, these samples of all these types and others are usually interpolated to create a surface representation. While there is a variety of interpolation algorithms (see Lam 1983; Burrough and McDonnell 1998), a few algorithms dominate the use in interpolation of agricultural data and will be discussed here. These commonly used algorithms, available in GIS software, include inverse distance weighting, spline methods, and kriging.

Inverse distance weighting is a linear interpolation method. It is implemented through the ideas of Thiessen polygons (Boots 1986) with a gradual change in a trend surface and uses weighted moving averages for computation of values at unknown locations. The basic concept is that data points are weighted by the inverse of their distance to the estimation point. This weighting has the effect of giving more influence to nearby data points than those farther away. Figure 59-5 shows the location of sample points within a field. Figure 59-6 shows the resulting interpolation for phosphorus (P) concentration using inverse distance weighting.

Splines are curves represented by piecewise polynomials that have continuous first and second derivatives. For interpolation purposes, the unknown points are fitted to the spline equation, but for geospatial data, this often requires fitting points to surfaces where the surfaces are represented with bicubic splines (Burrough and MacDonnell 1998). Figure 59-7 shows the same field from Figure 59-5 with P interpolated using bicubic splines.

A regionalized variable is one in which spatial variation can be expressed as the sum of three components: 1) a structural component having constant mean or trend; 2) a random, but spatially correlated component, which is the variation of the regionalized variable; and tic form prior to any

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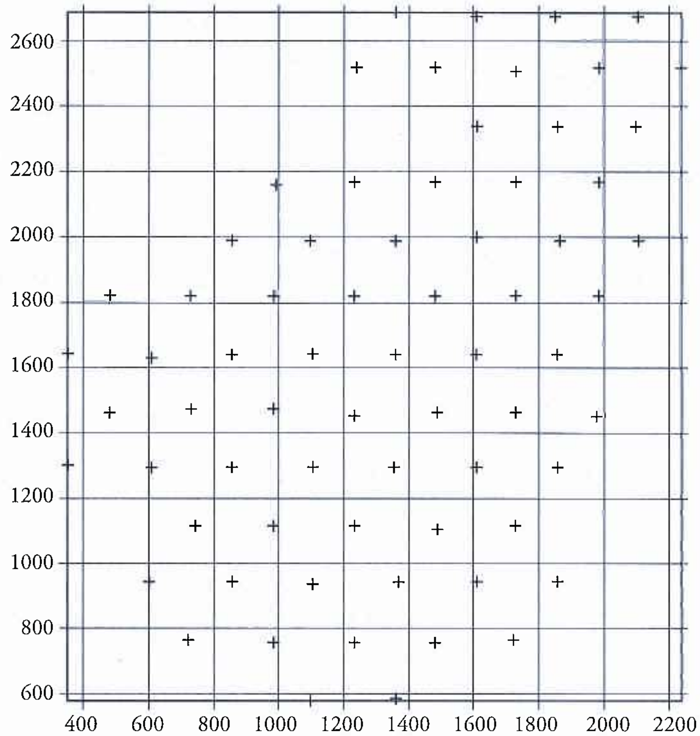

Figure 59-5 Soil sample locations to be used to interpolate a surface for phosphorus.

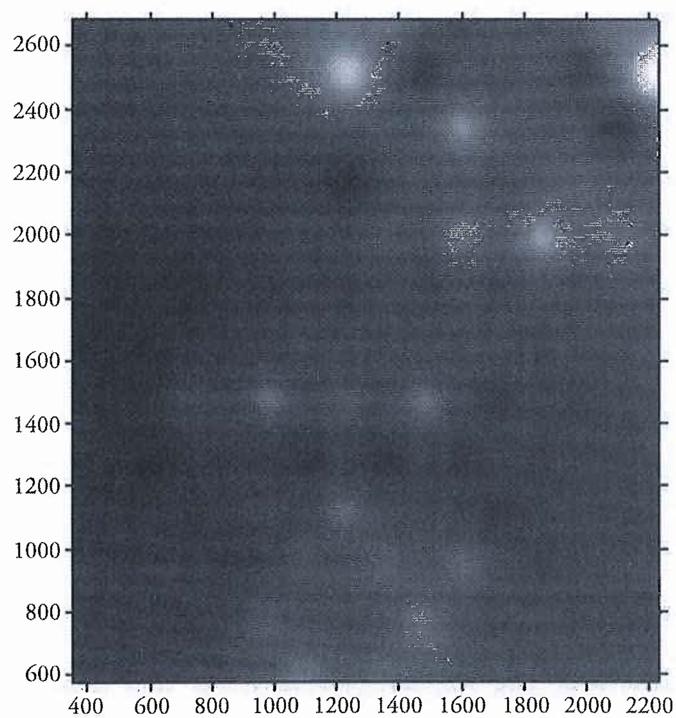

Figure 59-6 Inverse distance interpolation of phosphorus from the sample locations in Figure 59-5.

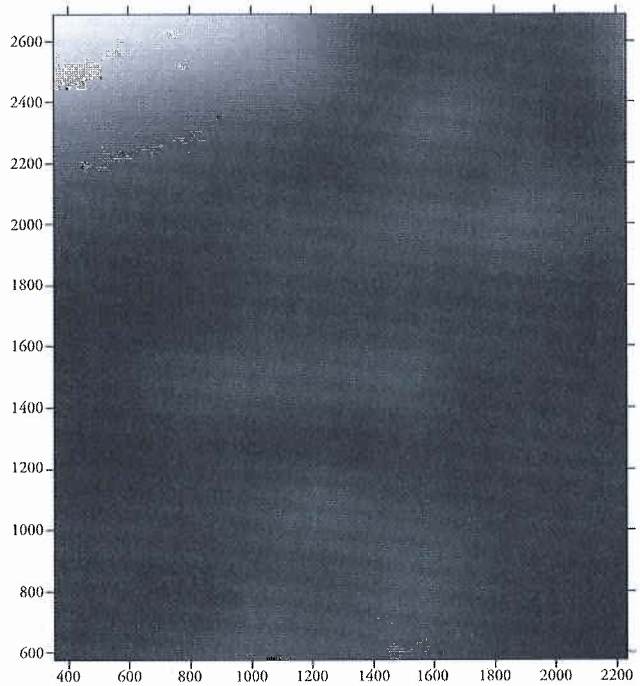

Figure 59-7 Spline interpolation of phosphorus from the sample locations in Figure 59-5.

3) random noise, which is a spatially uncorrelated residual error term. These variables are represented mathematically as:

$$Z(x) = m(x) + \varepsilon'(x) + \varepsilon'' \qquad (59\text{-}5)$$

where,

$m(x)$ is deterministic describing the structural component of Z,

$\varepsilon'(x)$ denotes the stochastic, locally varying but spatially dependent residuals from m(x), and

ε'' is residual spatially independent noise with zero mean and variance.

Using an assumption that the variances of differences in the attribute or Z value for a set of sample points depends only on the distance (lag or h) and direction between the points, i.e., intrinsic stationarity, an equation for the spatially dependent component called semivariance, $\gamma(x)$, can be developed. For details of the derivation of $\gamma(x)$, see Bailey and Gatrell (1995) and Burrough and MacDonnell (1998).

A plot of semivariance, $\gamma(x)$, from the sample data against the lag distance (h) called an experimental variogram provides a basis for quantitative description of regionalized variation. The variogram provides useful information for interpolation, sampling design, and determining spatial patterns. The key components of the variogram that provide information are the sill, range, and nugget, which provide parameter weights to control the kriging interpolation process. The sill is where the graph levels and implies that beyond these values of lag (h) there is no spatial dependence. The range is the rise from the lowest value to the sill and determines spatial dependence of the sample points. The range helps determine the window size to use in weighted moving averages. The nugget is the y-intercept and provides an estimate of ε'', representing spatially uncorrelated random noise. It is difficult or impossible to determine an appropriate set of weights for interpolating unknown points from the experimental variogram from the sample data, thus, a fit of one of several standard models is used. These standard models include the spherical, exponential, linear, and the Gaussian. The linear model is used when the graph never levels and the Gaussian is used for smooth variation and small nugget variance.

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For use of the variogram in spatial analysis and interpolation, one should not interpolate but use the mean value if the nugget dominates local variation. A noisy variogram indicates too few samples; usually 50 to 100 data points are required to get a stable variogram. The range determines optimum search window sizes. If a hole effect exists, i.e., a dip at distances greater than the range, this may indicate a periodicity effect or something similar. A large range shows long-range variation and if the Gaussian model fits, then smooth variation exists among the sample points and on the surface (Burrough and MacDonnell 1998).

As an example, Figure 59-8 shows the experimental variogram computed for P from the sample points for the field in Figure 59-5. Figure 59-9 shows the P values interpolated to a surface using kriging with weights determined from the variogram.

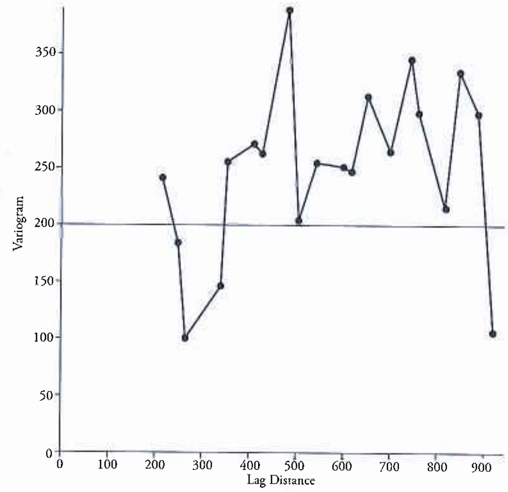

Figure 59-8 Experimental variogram from sample points in Figure 59-5.

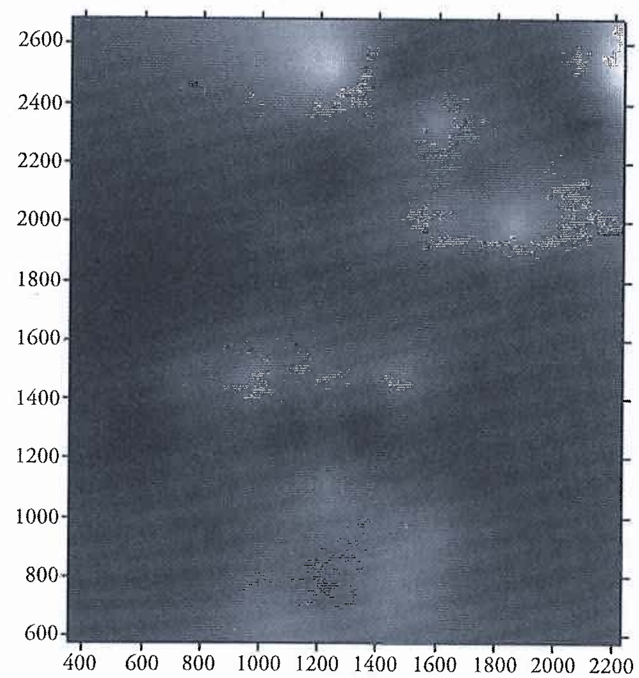

Figure 59-9 Kriging interpolation of phosphorus from the sample locations in Figure 59-5.

59.4.2.2 Spatial Modeling

One common approach for analyzing geospatial data is to create layers of single themes (thematic maps) of geographic phenomena and treat these layers as variables to which a set of operations can be applied. The approach is similar to mathematical algebra and is referred to as map algebra. Commonly, this approach uses a raster data model and each raster layer or map becomes a variable. A sequence of mathematical and spatial operators applied to the raster layers can be used to generate the desired output geospatial data set. The approach was developed by Tomlin (1984). The approach is flexible and allows a variety of operations to be completed to generate desired results. As with image processing operators, the map algebra operators are classified into three types: (1) point operators that work with single pixels, (2) neighborhood operators that work with a small group of pixels around the pixel of interest to determine the value of a single output pixel, and (3) global operators that use all pixels in the data set to determine the output.

The concept of map algebra can be used to implement a spatial modeling procedure referred to as *cartographic modeling.* Effectively a *cartographic model* is a sequence of map variables (layers) connected by map algebra operators that result in a spatial distribution of a particular geographic phenomenon. For example, a simple cartographic model can be implemented to use an elevation matrix to generate a slope map. The following equation shows the form of the operation:

$$\text{slope} = \text{differentiate (elevation)} \qquad (59\text{-}6)$$

where,

slope is the resulting map of slope,

differentiate is the function that determines the first derivative of the elevation surface at each point, and

elevation is the elevation map.

Note that the *differentiate* operator only requires a single operand and is commonly implemented as a finite difference approximation on a pixel neighborhood basis (often a 3 x 3 filter) on a grid-based elevation matrix.

The Universal Soil Loss Equation (USLE) can be implemented as a cartographic model. Six parameters are combined to determine an estimate of soil loss as shown in the following equation.

$$A = R * K * L * S * C * P \qquad (59\text{-}7)$$

where,

A is the annual soil loss in tons/ha,

R is the erosivity of rainfall,

K is the erodibility of the soil,

L is the slope length in meters,

S is the slope in percent,

C is the cultivation parameter, and

P is the protection parameter

If we develop a raster data layer for each of the parameters for a particular watershed area and place them in a multiplicative model (Figure 59-10), we can compute an estimate of the soil loss for the watershed.

We can also use a cartographic model to determine the profit potential for growing a particular crop. An example for profit from growing coffee is provided in Burrough (1986). In the example, the price of coffee is determined from the suitability of the soil while the price is modified by transportation costs, which are determined from distance to a road and the terrain.

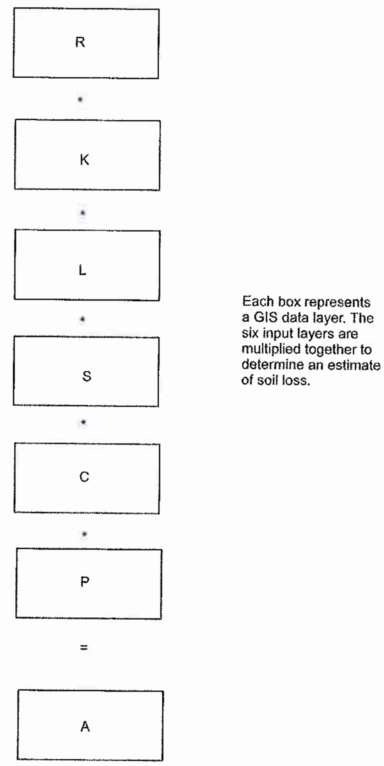

Figure 59-10 Cartographic model of the Universal Soil Loss equation.

59.5 Precision Agriculture

In theory, precision agriculture is a management philosophy that espouses matching inputs to exact needs everywhere. It is commonly referred to by other names such as precision farming, farming by the foot, farming by satellite, site specific management and target farming. In reality, many practices often are grouped under the banner of precision agriculture whose only common link is a reliance on advanced geospatial technologies.

Precision agriculture allows measuring and characterizing spatial variability, thereby aiding our ability to manage that variability. Management decisions may aim to overcome the variability through variable rate application of inputs, tolerate the variability, if for instance the cost of remedial action is too high, or enhance the variability through management practices that optimize the yield potential of different areas within a field. Variation is a feature of all farming systems and may be both spatial and temporal. Spatial variability results from changes in physical properties, such as soil type, texture, moisture and fertility. In addition to spatial variability, variability exists from season to season. Seasonal changes, temporal variations, are usually driven by unforeseen factors such as the weather, which in non-irrigated environments can be extremely challenging to manage.

In the United States precision agriculture began to emerge in the early 1990s (Usery et al. 1995). Although research into field spatial variability dates back considerably further, it was not until the maturation of several enabling technologies that precision agriculture began to take shape. For examples of precision agriculture projects see NESPAL (2008b).

59.5.1 Yield Monitoring

A yield monitor is a device that is mounted on crop-harvesting machines that measures yield as the crop is harvested. A yield monitor consists of several components, including a variety of sensors that measure harvester parameters, a yield sensor and a GPS that provides positional information. The GPS readings are coupled to the sensory measurements and logged to an on-board computer. A yield monitor quantifies the variability in yield and enables the generation of a thematic map, which highlights spatial variability. Yield monitors are commercially available for most major row crops (Figure 59-11) and have wide acceptance in the agricultural community, particularly for grain production.

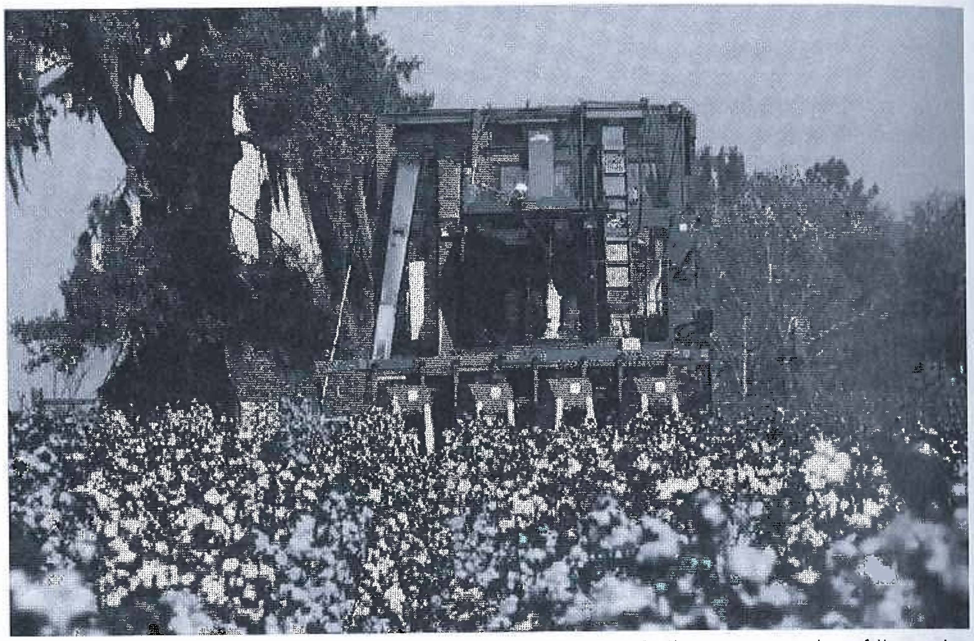

Figure 59-11 Yield monitor for cotton. Note the GPS antenna in the upper center of the cotton picker. Courtesy: NESPAL. See included DVD for color version.

Yield monitors function by measuring either the volumetric or mass flow of material. Crop mass is measured by weighing the material in a basket or bin, or measuring the mass flow rate of the material as it passes a specific point on the harvester. Weighing techniques are straightforward and utilize load cells to measure the change in weight as the crop is harvested. Load cell designs are used to monitor peanut, citrus and vegetable crops.

There are several techniques employed to measure the mass of material as it is being transported through a section of the harvester. Grain harvesters have employed three primary methods. One utilizes an impact plate that measures the force exerted by material as it exits the grain elevator. Another is a technique that bombards radiation onto the cross-section of flowing grain. A receiver on the other side receives radiation after interacting with the flow of material. Changes in the transmitted radiation is measured and correlated to yield. Radiometric sensors are commonly used in European harvesters but are not available in the United States. A third technique involves a capacitive sensor that detects the dielectric changes in the mass of material as it passes capacitive plates. The dielectric properties are sensitive to moisture and foreign materials, which must be taken into account if the sensor is to be accurate.

Light-based techniques have become popular in measuring yield on mechanical cotton pickers. In this method, light-emitters are placed on one side of the air duct and photodiodes (light detectors) on the opposite side. As cotton flows through the duct, the beam of light to the detectors is broken. The mass of material is then correlated to the amount of time the light beam is broken between the emitter and detector.

The principle behind volumetric measurement is based on filling a compartment of a known volume and then releasing that volume into a bin or basket. There are two principle systems used. The first relies on a paddle wheel mounted below the discharge spout on a clean grain elevator. A level sensor above the paddle wheel indicates when the grain has filled to a specific depth. The wheel then rotates, drops one load of grain, and begins accumulating another load. The rate at which the paddle wheel turns is correlated to the yield. The second type of volumetric measurement technique employs a light detector that indicates the volume of grain on a grain elevator rotation. The yield is calculated from the speed of the grain elevator and the volume of each rotation.

59.5.2 Variable Rate Technology and Variable Rate Irrigation

59.5.2.1 Variable Rate Technology

Variable rate technology (VRT) refers to any equipment designed to allow the rate of farm inputs to be precisely controlled and varied while the machine is in operation. There are two types of variable rate technology: map-based and real-time sense and treat. Map-based VRT is most widely used and requires a GPS receiver, computer controller and a regulated drive mechanism mounted on the applicator. Application rates are preprogrammed into computer memory using information collected prior to the application. Maps are based on soil tests, aerial photographs, or other information collected prior to application. The GPS provides positional information that is used to determine the appropriate application rate. Equipment such as planters, fertilizer spreaders and liquid sprayers can be equipped to vary single or multiple inputs simultaneously.

Real-time sense and treat systems are dynamic systems that use a sensor to measure a physical or crop property and apply an input in response to this measurement. These systems are often used in weed control using an optical sensor to measure the presence or absence of weeds within a crop. Other optical systems use the reflectance properties of plants to measure crop reflectance and create a vegetative index that is used to vary the application of crop inputs such as nitrogen and growth regulators.

Precision farming recognizes the concept that agricultural fields are not uniform. Many fields will have variable topographic and soil conditions that will result in variability in biophysical parameters such as crop growth, weed and pest infestations and yield. Yield mapping, remote sensing, and intensive soil sampling are frequently used to characterize the variability present. This information can be extremely informative in gaining an understanding of the underlying agronomic processes within a field. The value of this insight hinges on how we can utilize the information.

This is where variable rate application technology (VRA or VRT) offers value. The use of VRT enables the rate of farm inputs to be precisely controlled and varied while a machine is in operation. This often involves the use of a combination of electronic controllers and variable rate pumps, motors, or valves, however this need not be the case. However, VRT may rely on a low technology solution where the operator manually adjusts the rate or application of inputs based on cues he/she detects with his/her own senses and expert knowledge of the field.

There is a large volume of research examining variable rate fertilizer applications, particularly in grain cropping systems. Issues that need to be addressed when developing a method for varying fertilizer application within a field include the cost, time, and complexity of variable rate application. Studies have long supported the common sense notion that soil fertility can vary tremendously between regions within a field. Site-specific nutrient management can offer economic rewards as long as manageable nutrient variability exists in the field.

The concept of spatially matching soil fertility inputs to field needs requires a knowledge of how the fertility varies, and hence a soil sampling strategy. Unlike the general concept, the choice of sampling pattern has probably been the most controversial issue in precision agriculture. In the early 1990s two lines of thought arose around the opposing theories of grid sampling and directed sampling. In the beginning the proponents of grid sampling achieved a strong following and soon this methodology was widely practiced. Grid sampling became synonymous with soil sampling for precision agriculture. Over the past several years, however, grid sampling has fallen from favor. The far more rational, flexible, and economically viable strategy, known as directed sampling (along with the associated concept of "zone management"), currently prevails as the method of choice (Pocknee 2000).

To implement a directed sampling scheme requires a field to be divided into zones of similar fertility. The delineation of these zones can be achieved in many ways but often involves the use of yield maps, aerial photos, soil maps, farmer knowledge, and field topography. The resultant map is used to direct the location of individual soil samples. A composite sample from each zone is analyzed and an application map can be generated using these results along with yield goals that are assigned to each zone. If soil test results do not indicate significant differences in nutrient levels between zones, variable rate application may not be warranted.

Management zones must be analyzed, evaluated and adjusted over time. They are not static and will change as the management style and capabilities of the farmer change. It may be prudent to combine zones that consistently perform similarly over time and to split zones that show more variability than initially thought. Changes in equipment must also be considered and may require an adjustment to zones.

Crucial to any variable rate application is the need to assess the response or outcome to the treatment. Measuring a response to different treatments requires on-farm experimentation. To optimize production for economic and environmental benefits, it is necessary to develop response functions to fertilizer. Variable rate technology coupled with yield mapping enables farmers complete flexibility in on-farm testing. Farm experimentation may be as simple as a strip plot design where test strips run the length of the field, or may be a sophisticated randomized block design where treatments are applied to the management zones of the field.

59.5.2.2 Variable Rate Irrigation

Variable-rate irrigation (VRI), also called site-specific or precision irrigation, is a relatively new concept in agriculture. VRI is a tool that involves the delivery of irrigation water in amounts that match the needs of individual areas within fields.

Most center-pivot (CP) irrigation systems currently in use apply a constant rate of water. Some systems can provide variable application rates in wedge-shaped sections of a field by varying the travel speed of the system through those areas. However, the ability to vary application rates over randomly shaped zones has not been possible with normal systems. Recent advances in technology and the availability of a commercial system has changed this. VRI can now deliver the appropriate amount of irrigation water to each area in a field. This is achieved by a combination of pivot speed control and cycling sprinklers on and off.

Variable soil properties and topography will cause corresponding variations in soil water properties such as water holding capacity, drainage rates, and infiltration rates. Many CP systems do not make complete circles nor overlap other pivots. Similarly, many CP systems have areas, such as waterways, ditches, ponds, or roadways, that are not cropped and do not need to be watered. Other fields may be irregularly shaped or contain multiple crops. All of these scenarios can benefit from a system with the ability to apply varying amounts of irrigation water to specific areas in a field.

One should not immediately assume that they must purchase new hardware to implement VRI. Some things that can be done inexpensively include:

- dividing a pivot into pie sections with different water needs and manually changing the pivot travel speed through the sections (this can also be done with newer control panels)
- using end-gun controls more effectively

- using manual valves to turn off individual sprinklers
- installing VRI controls on only part of a pivot, rather than on the entire pivot

High-resolution true-color images are a valuable tool for assessing a field's suitability for VRI. Images are an excellent low-cost tool that can aid the characterization of within-field variability, and identify and quantify features such as non-cropped intrusions or inclusions in a field. Non-cropped areas are parts of a field that are not planted such as ponds, depressed areas, roads, areas of trees and drainage lines. These areas are under the coverage of the irrigation system but do not require water. Using rectified images, the non-cropped areas of a field can be quantified and estimates of water savings using a VRI system calculated. Although this information needs to be ground-truthed by a site visit, this approach enables a quick assessment and screening tool for determining a field's suitability for VRI and the potential water savings. Developing a water application map for the VRI controller requires the assimilation of available spatial data such as yield maps, aerial photos, soil survey maps, and first-hand knowledge of the field to develop watering management zones.

In most agricultural systems around the world, the primary input driving crop production is water. Irrigation is a necessary part of many cropping systems due to insufficient or uneven rainfall. The potential for an irrigation system that delivers optimum amounts of irrigation water over an entire field is significant.

In the US there are approximately 150,000 center pivots watering over 21 million acres of cropland. In all parts of the US, agriculture is putting increased demands on limited water resources. Droughts and lawsuits have prompted a renewed interest in water conservation methods by the general public, which is becoming increasingly insistent that agriculture participate in conserving water. Studies on over 25 VRI pivots installed in Georgia have shown a 12–16% reduction in water use while increasing yield (NESPAL 2008a). The main savings were achieved through improved control of the system, allowing sprinklers to be turned off over non-cropped regions (ponds, drainage areas, field roads, etc.) within the field and bordering areas.

59.6 Soil Sampling, Mapping and Imaging

Geographic representations of soils have existed since 1899 when the US Department of Agriculture developed the soil survey program to help farmers evaluate suitable cropping and management practices for the soils on their farms. As more was learned about soils, the soil survey information was applied to other land uses. Modern soil surveys are used for many activities, such as highway construction, farm planning, tax assessment, forest management and ecological research, in addition to agriculture. Accurate soil descriptions are critical for many investigations related to land responses to natural and man-induced inputs.

Aerial photography has been used as an aid for soil mapping and a presentation base for the final maps since the 1920s. The use of these maps has greatly increased the precision of soil surveys and permitted extensive mapping at detailed scales (1:24,000 or greater). These map-based soil surveys have naturally evolved into geographic representations that can be integrated into GIS to make comparisons between soils and other geographic characteristics.

Soil surveys for most counties throughout the US were compiled by the National Cooperative Soil Survey (NCSS). The NCSS is a joint effort of the US Department of Agriculture (USDA) and other federal agencies, along with many state agencies and local agencies. County-level soil surveys have been available since the 1900s and refined surveys are still being developed. Currently, two levels of soil survey are available in GIS. These include the State Soil Geographic (STATSGO) data and the Soil Survey Geographic (SSURGO) data. The two data sets vary considerably in their level of detail and their availability. Both data sets can be downloaded from the USDA Natural Resources Conservation Service (NRCS) geospatial data gateway (USDA 2008a).

The STATSGO data are produced by generalizing the detailed county-level soil survey data. The mapping scale for STATSGO is 1:250,000 (with the exception of Alaska, which is 1:1,000,000). The minimum area mapped is approximately 625 ha (1,544 acres). The level of mapping provided in the STATSGO database is designed to be used for broad planning and management uses covering state, regional, and multi-state areas. The STATSGO data are available for the conterminous US, Alaska, Hawaii, and Puerto Rico. Digitizing of the STATSGO data is done in line segment (vector) format in accordance with NRCS digitizing standards. Map unit delineations match at state boundaries. Composition of soil map units was coordinated across state boundaries, so that component identities and relative extents would match. The STATSGO data are available in the USGS Digital Line Graph (DLG-3) optional distribution format. They are also available in ArcInfo 7.0 coverage and GRASS 4.13 vector formats (http://datagateway.nrcs.usda.gov/).

Each STATSGO map is linked to the Soil Interpretations Record (SIR) attribute database. The attribute database gives the proportional extent of the component soils and their properties for each map unit. The STATSGO map units each consist of 1 to 21 components. The SIR database includes over 25 physical and chemical soil properties, interpretations, and productivity. Examples of information that can be queried from the database are available water capacity, soil reaction, electrical conductivity, and flooding; building site development and engineering uses; cropland, woodland, rangeland, pastureland, and wildlife; and recreational development.

The SSURGO data are substantially more detailed than the STATSGO data. Mapping scales generally range from 1:12,000 to 1:63,360. The SSURGO data are the most detailed level of soil mapping done by the NRCS. Digitized SSURGO maps duplicate county-level soil survey maps and provide the data in GIS format. This level of mapping is designed for use by landowners, townships, and county natural resource planning and management. The SSURGO data are currently only available for selected counties and areas throughout the US (USDA 2008b). Completion of the SSURGO database is expected in 2008.

As with STATSGO, digitizing of the SSURGO data is done by line segment (vector) format in accordance with NRCS digitizing standards. The mapping bases meet national map accuracy standards. SSURGO data are distributed as a complete coverage for a soil survey area. The SSURGO data are linked to a National Soil Information System (NASIS) attribute database. The attribute database gives the proportionate extent of the component soils and their properties for each map unit. The SSURGO map units consist of 1 to 3 components each. Examples of information that can be queried from the database are available water capacity, soil reaction, electrical conductivity, and flooding; building site development and engineering uses; cropland, woodland, rangeland, pastureland, and wildlife; and recreational development.

The map extent for a SSURGO data set is a single soil survey area, which may consist of a county, multiple counties, or parts of multiple counties. A SSURGO data set consists of map data, attribute data, and metadata. SSURGO map data are available in ArcView shape files, ArcInfo coverages, and ArcInfo interchange file formats. The coordinate systems are geographic, UTM, and SPC. Attribute data are distributed in ASCII format and can be imported into a Microsoft Access database. Metadata are in ASCII and XML format.

59.7 Watershed Management, Analysis and Modeling

59.7.1 Watersheds and Watershed Management

A watershed is a geographic area that drains into a single stream or river because of topography. John Wesley Powell defined it as "that area of land, a bounded hydrologic system, within which all living things are inextricably linked by their common water course and where, as humans settled, simple logic demanded that they become part of a community."

Watersheds are separated by topographic ridges dividing the drainage systems. Because watersheds often contain different geologic features and differences in climate, they can often be used to divide regions for analysis and management purposes. Watersheds are important for drought and flooding investigations, as legal points of reference when dealing with water rights, and for managing the quality of the water contained therein. Since large watersheds are made up of many smaller watersheds, it is necessary to define the watershed in terms of a point of reference in the stream. This point is referred to as the watershed outlet. With respect to the outlet, the watershed consists of all the land area that sheds water to the outlet during a rainstorm. A watershed is defined by all points enclosed within an area from which rain falling at these points will contribute water to the outlet. Surface and groundwater flow patterns are not always defined by the same boundaries. Thus, watersheds defined by their surface drainage patterns and those defined by their subsurface drainage patterns are not always the same.

Human modifications of lands and waters directly alter delivery of water, sediments, and nutrients. Any activity that changes soil permeability, vegetation type or cover, water quality, quantity, or rate of flow at a location can change the characteristics of a stream or even the watershed at downstream locations. Land use practices such as clearing land for timber or agriculture, developing and maintaining roads, housing developments, and water diversions may have environmental consequences that greatly affect stream conditions even when the land use is not directly associated with a stream. Proper planning and adequate care in implementing projects can help ensure that one activity within a watershed does not detrimentally impact the downstream environment.

Because of similar climatic, geographic, and land management conditions within watersheds and their natural ties to communities, they often represent the most logical basis for managing water resources. The water resources within the watershed become the focal point for management considerations. Managers are able to gain a clearer understanding of the overall conditions in an area and the stressors that affect those conditions by examining the watershed as a whole. Watershed management can offer a stronger foundation for uncovering the many stressors affecting a watershed. The result is a better assessment of the actions required to protect or restore the resource. Because of these factors, watersheds, and hydrologic models that describe surface and subsurface flow within these watersheds, are commonly used for land management decisions.

Watersheds often contain similar vegetation, crop production, soils, topography, and climatic patterns. Increasingly state agencies are turning toward watershed management as a means of achieving water quantity and quality goals. Land owners can be organized because they often share similar production methods and goals. Because watersheds are defined by natural features, they represent a logical basis for managing natural resources. Conditions that affect the overall state of the watershed can often be recognized and addressed in a consistent manner. Watershed management provides a framework for integrated decision making, where we strive to: (1) assess the nature and status of the watershed; (2) define short-term and long-term goals; (3) determine objectives and actions needed to achieve selected goals; (4) assess both benefits and costs of each action; (5) implement desired actions; (6)

evaluate the effects of actions and progress toward goals; and (7) re-evaluate goals and objectives as part of an iterative process.

Besides the environmental pay-offs, watershed approaches can have the added benefits of saving time and money. Whether the task is monitoring, modeling, issuing permits, or reporting, a watershed framework offers many opportunities to simplify and streamline the workload. Efficiency is increased by providing a common focus and resources can be pooled to focus on a single geographic area. By coordinating their efforts, agencies can complement and reinforce each others' activities, avoid duplication, and leverage resources to achieve greater results.

Watershed protection can lead to greater awareness and support from the public. Once individuals become aware of and interested in their watershed, they often become more involved in decision making as well as hands-on protection and restoration efforts. Through such involvement, watershed approaches build a sense of community, help reduce conflicts, increase commitment to the actions necessary to meet environmental goals, and ultimately, improve the likelihood of success for environmental programs.

However, land traditionally has often been managed at a very local scale. Changes in land management historically were, and still largely are, implemented by private land owners with little regard to the location of the managed land in relation to other parcels of land. While very effective at the local field scale, these types of management implementation policies often have a very localized impact and make it difficult to obtain larger, regional impacts. People have varying goals and values relative to uses of local land and water resources. Overcoming the obstacles created by private land management requires time and an understanding of the motivation of the land owners. Watershed management requires use of the social, ecological, and economic sciences. Common goals for land and water resources must be developed among people of diverse social backgrounds and values. The decision process must weigh the economic benefits and costs of alternative actions, and blend current market dynamics with considerations of long-term sustainability of the ecosystem.

Watershed management is an iterative process of integrated decision making regarding uses and modifications of lands and waters within a watershed. This process provides a chance for stakeholders to balance diverse goals and uses for environmental resources, and to consider how their cumulative actions may affect long-term sustainability. As a form of ecosystem management, watershed management encompasses the entire watershed system, from uplands and headwaters, to floodplain wetlands and river channels. It focuses on the processing of water, sediments, nutrients, and toxics downslope through this system. Of principle concern is management of the watersheds' water budget, which is the routing of precipitation through the pathways of evaporation, infiltration, overland flow, groundwater recharge, and groundwater discharge (Woolhiser 1982). This routing of groundwater and overland flow defines the delivery patterns to particular streams, lakes, and wetlands and largely shapes the nature of these aquatic systems.

59.7.2 Watershed Modeling

Because of the complex nature of watersheds and the many factors related to watershed management, it is often useful to incorporate a watershed model into the process. A watershed model is an abstraction of the natural processes. Representation of the natural system obviously requires simplification. This simplification allows managers to place the system into a manageable context, which can be used to examine the impact of different conditions on watershed processes.

Models can take many shapes and forms. They can be mathematical representations of the natural processes or physical prototypes of the watershed. For more complex examinations, mathematical models are typically used. Mathematical models can be empirical, based largely upon observed data, or theoretical, based upon mathematical representations of the physical processes occurring within the watershed. Empirical models can be very useful if an extensive data base of observed data is available. An empirical model is a mathematical representation of the observed data. In reality, most physically based watershed models contain empirical components because of the complexity of the natural system.

Management of watersheds with the goals of balancing the needs of the general public with environmental concerns in those regions often requires complex descriptions of the processes occurring therein. Significant advances have been made with physically based watershed models with the advent of modern computer systems and GIS. These watershed models can incorporate many of the natural geologic and climatic features into the modeling system by making full use of the GIS packages. These models allow a very thorough examination of the impact of watershed scale management on the quantity and quality of water within the watershed. Several reviews of watershed models have been previously published (Singh and Frevert 2005, 2002a, b; Singh 1995; Parsons et al. 2001). The accuracy of the models has improved with the introduction of computers and the capacity that they brought to increase the level of complexity of these models.

Many currently available models are physically based, attempting to describe the geophysical processes occurring on the landscape with mathematical equations. These models require considerable input data, most of which is spatially related. Physical characteristics of watersheds, such as the soil, topography, and land use, vary spatially. GIS allows spatial representation of the features, improving the accuracy of the watershed models. Many watershed models have quickly adapted to using the geographical data handling capabilities of GIS, both to ease the development of input data sets and for the analysis of model output. The GIS allows the compiling and processing of these input data sets with relative ease and significantly reduces the rather cumbersome task of assembling input data for large-scale watershed models.

Several watershed models have been developed and modified to take advantage of GIS databases. The models that best utilize the full capabilities of the GIS are classified as distributed models. Distributed models attempt to explicitly account for the variability of processes by varying the input, boundary conditions, and watershed characteristics through space. Because it is impossible in practice to capture the full variability of natural processes, all distributed models perform some degree of lumping, or simplification, with the input characteristics.

The assembly of the distributed climatic, geologic, and land use data necessary for accurately representing characteristics in the watershed can become an insurmountable task. However, the ability of the GIS to extract, overlay, and delineate watershed characteristics greatly simplifies the development of the input information. Integration of GIS with watershed modeling accomplishes several functions, namely, design, calibration, modification, and comparison of watershed models. These systems also facilitate watershed division so that specific sections of the watershed can be modeled. GIS also facilitates closer examination of relationships between model outputs and the spatial characteristics of the watershed.

A few of the commonly used Watershed Models that utilize GIS are briefly discussed here. This review is provided as illustration of the tools and not as a complete description of this topic. For additional discussions on the topic the reader is guided to texts that focus solely on Watershed Models (Singh and Frevert 2005, 2002a, b; Singh 1995).

59.7.2.1 AGNPS and AnnAGNPS

The single event Agricultural Non-Point Source (AGNPS) model was developed in the early 1980s by the Agricultural Research Service (ARS) in cooperation with the Minnesota Pollution Control Agency, and the Natural Resource Conservation Service (NRCS) (Young et al. 1989, 1995). The model was developed to analyze and provide estimates of runoff water quality resulting from single storm events from agricultural watersheds ranging in size from a few hectares to 20,000 ha. The AGNPS model is grid or raster based. The grid-based cells were used to track surface drainage patterns throughout the watershed. The use of grid cells led to adaptation of the model into several GIS platforms (Mitchell et al. 1993; Srinivasan et al. 1994; Rode et al. 1995; Tim and Jolly 1994).

In the early 1990s, a cooperative team of ARS and NRCS scientists was formed to develop an annualized continuous-simulation version of the model, AnnAGNPS (Cronshey and Theurer 1998). AnnAGNPS is the pollutant-loading component for a suite of models referred to as AGNPS 2001. AGNPS 2001 includes GIS routines for developing model input and analysis of model output. The GIS tool automates many of the input data preparation steps needed for use with large watershed systems. Interfaces have been developed to facilitate the use of GIS and the AnnAGNPS model (Xiao 2005).

59.7.2.2 SWAT

SWAT is a river basin model developed to quantify the impact of land management practices in large watersheds (Arnold et al. 1998). SWAT was a modification of the Simulator for Water Resources in Rural Basins (SWRRB) model (Williams et al. 1985). SWAT was developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large watersheds with varying soils, land use, and management conditions over long periods of time. The major components of the model include hydrology, weather, erosion and sediment transport, soil temperature, crop growth, agrichemical transport, and agricultural management. The model has been successfully applied on watersheds up to 598,538 km^2 in area (Srinivasan et al. 1997).

To facilitate data input for these large areas, GIS tools have been developed for SWAT (Di Luzio et al. 2004). Currently SWAT 2000 is incorporated into AVSWAT-2000, an ArcView extension and a graphical user interface for the model (Di Luzio et al. 2004). The GIS framework simplifies input development and output analysis. The interface can be used to: 1) generate specific parameters from user-specified GIS coverages; 2) create SWAT input data files; 3) establish agricultural management scenarios; 4) control and calibrate SWAT simulations; and 5) extract and organize model output data for charting and display (Di Luzio et al. 2002). The GIS tool also includes features to delineate the watershed drainage.

59.7.2.3 BASINS

The US EPA and its counterparts in states and pollution control agencies are increasingly emphasizing watershed assessments. To facilitate this, the EPA developed the Better Assessment Science Integrating point and Nonpoint Sources (BASINS) system (US EPA 2007). BASINS integrates a geographic information system (GIS), national watershed and meteorological data, and state-of-the-art environmental assessment and modeling tools into one software package. BASINS contains three models for estimating watershed loading. These models include a simplified GIS-based nonpoint-source loading model (PLOAD) and two physically based watershed loading and transport models, Hydrologic Simulation Program-Fortran (HSPF) and SWAT.

59.8 Conclusions

Application of advanced information technologies to agriculture and watershed management has become standard procedure for many farmers, agronomists, and hydrologists. The improvements brought by these technologies include precise positioning allowing determination of nutrient, herbicide, and pesticide needs on a variable infield basis. The same positioning allows determination of yields for exact portions in a field so that correct amounts of inputs can be applied to improve yields and minimize environmental degradation. Watershed modeling has been improved since inputs to models can now be automatically generated and finer resolution data can be used to produce better models of watershed activity. The technologies of GPS, remote sensing, GIS and VRT provide a significant advance to agriculture and watershed managers and a return to the public through improved agriculture with reduced environmental damage.

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