9

Introduction to Remote Sensing and GIS

Remote sensing, the geotechnology that includes the processing, manipulation, and analysis of analog and digital images collected using devices that are not in contact with the Earth, has become one of the driving forces behind the rapid growth of GIS in the past few decades. Remote sensing analysts, a specialized category of geospatial professionals, produce stunning visualizations of environmental and human processes such as climate change, natural resource exploitation, and sprawling urbanization using a vast and growing catalog of digital satellite imagery. Digital image processing and a steady stream of new sensors and airborne platforms (built upon a strong foundation of over 100 years of mapping using aerial photography and photogrammetry) have resulted in powerful automated and reliable methods of big data visualization, analysis, and knowledge creation (Figures 9.1 and 9.2).

9.1 Remote Sensing Fundamentals

Remote sensing can be thought of as a linear process that begins with an electromagnetic radiation (EMR) source, commonly designated as passive or active (see Figure 9.3). Passive energy sources exist in nature such as solar radiation from the sun or thermal emission (heat) from Earth. Most remote sensing relies on passive energy sources. An active energy source is human-produced and generated by a sensors. Active remote sensing includes radar scanners (using microwave pulses), LiDAR (using laser pulses in the visible and infrared), and even ordinary flash cameras. In passive remote sensing using solar radiation, before the EMR reaches Earth it must pass through the atmosphere where it may be partially absorbed or scattered by different atmospheric components (see Figure 9.3b). This has the effect of reducing the amount of EMR that reaches the Earth's surface, and occurs selectively across the visible and IR spectrum depending upon wavelength. The electromagnetic spectrum, a graphical representation of electromagnetic energy categorized by wavelength, is a useful tool for characterizing energy by wavelengths (Figures 9.4 and 9.5).

Upon striking the Earth's surface EMR is either reflected, transmitted, or absorbed. It is reflected selectively by wavelengths depending on the type and condition of any surface or material that is illuminated. Because the surface

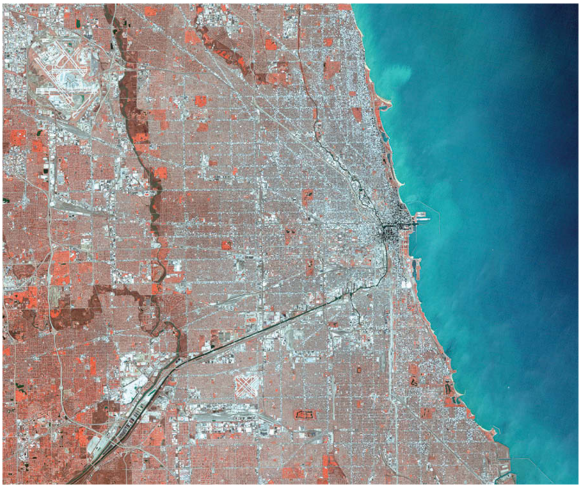

FIGURE 9.1
Chicago, Landsat 5 Thematic Mapper (TM) 24-bit color composite, channels 4–2–1, red–green–blue, April 15, 2008. This classic false-color IR image shows substantial turbidity (vivid turquoise) in Lake Michigan, and moderately robust vegetation (bright red) in lakeshore and suburban parkland.

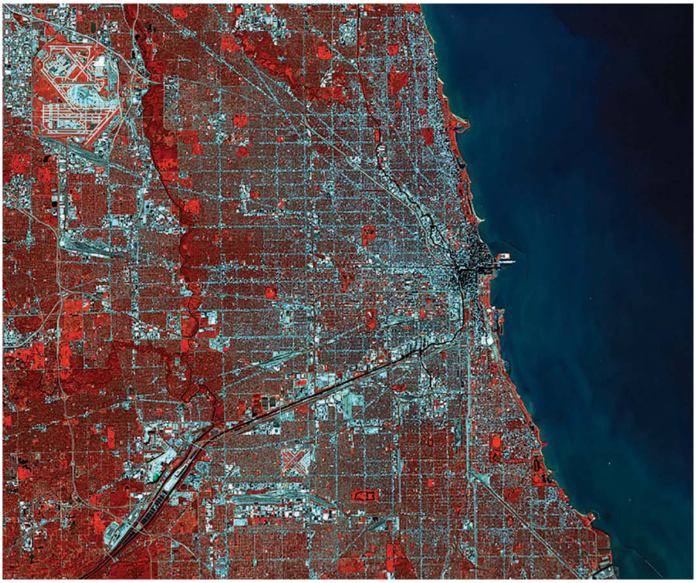

FIGURE 9.2
Chicago, Landsat 8 Operational Land Imager (OLI) 24-bit color composite (scaled from 48-bit raw data), channels 5–3–2, red–green–blue, October 14, 2016. Notice the much more robust irrigated early autumn vegetation, lower lakeshore turbidity, and substantial expansion of O'Hare Airport. 48-bit OLI data scaled to 24-bit for VGA display.

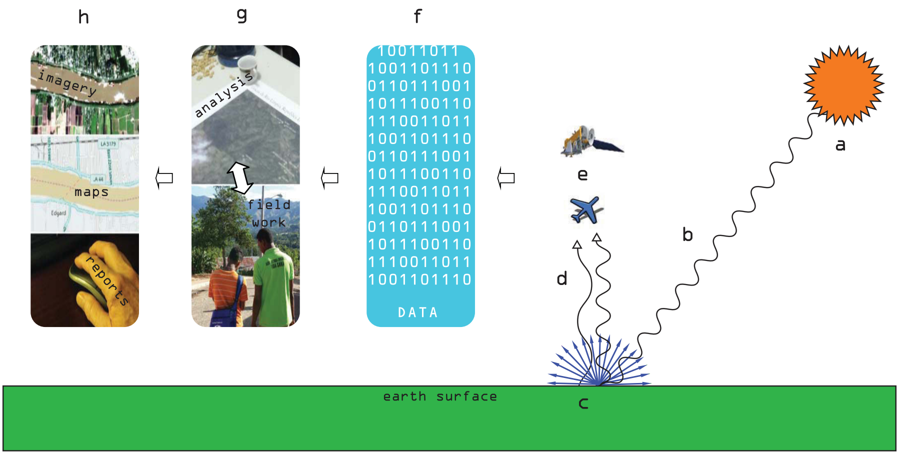

FIGURE 9.3
Remote sensing using passive sensors, depicted as a linear process.

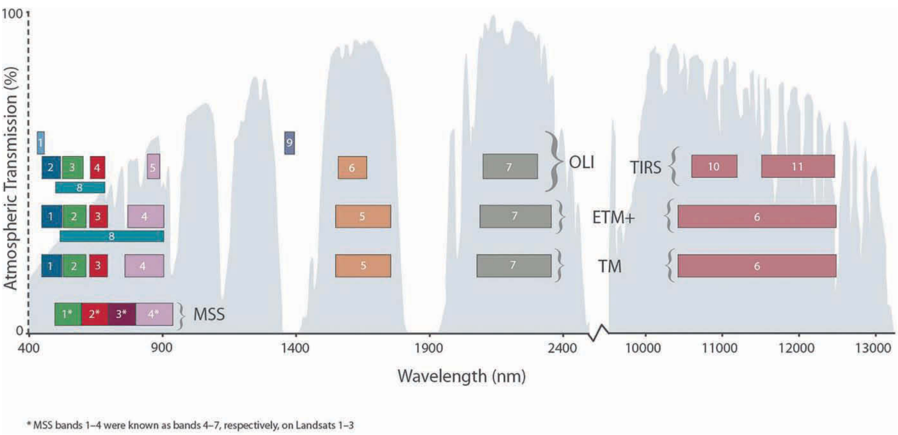

FIGURE 9.4
Percentage of atmospheric transmission by wavelength (nm), Landsat multispectral sensor channels, 1972 to present.

of Earth is two-thirds water, EMR may be transmitted through the water depending on its clarity, and in shallow water, it may strike a surface and be reflected back into the atmosphere. Any surface can also absorb EMR raising its temperature, and this energy can be released over a period of time as longer-wavelength thermal IR EMR. Because different surfaces reflect energy differently depending on wavelength, we can characterize the reflectance of different surfaces and materials using a spectral reflectance graph (see Figure 9.6). When EMR strikes a surface it tends to reflect in a diffuse manner, but reflection in nature is never perfectly diffuse and normally contains

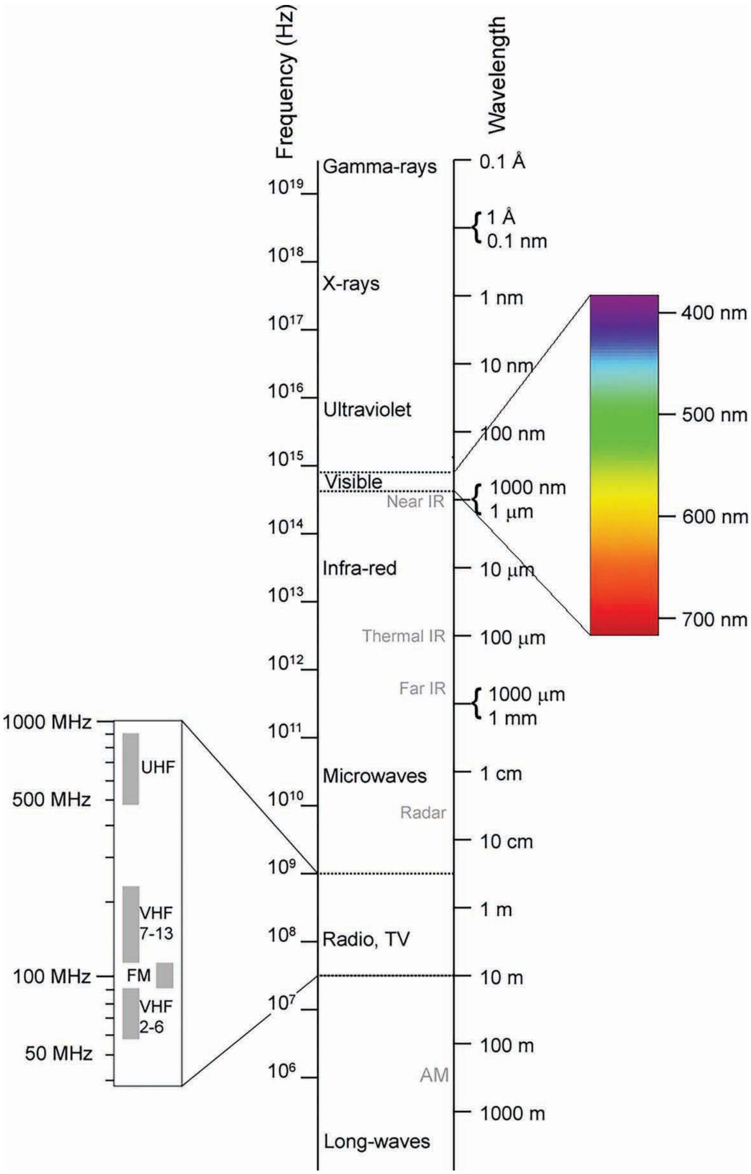

FIGURE 9.5
Electromagnetic spectrum.

a specular or mirror-like component. Diffuse reflectance from a flat surface can be thought of as exiting that surface around a hemispherical space with uneven levels of reflectance in particular directions, normally biased at the angle equal and opposite to the solar azimuth and elevation. Remote sensing instruments normally target diffuse reflectance in the vertical angle.

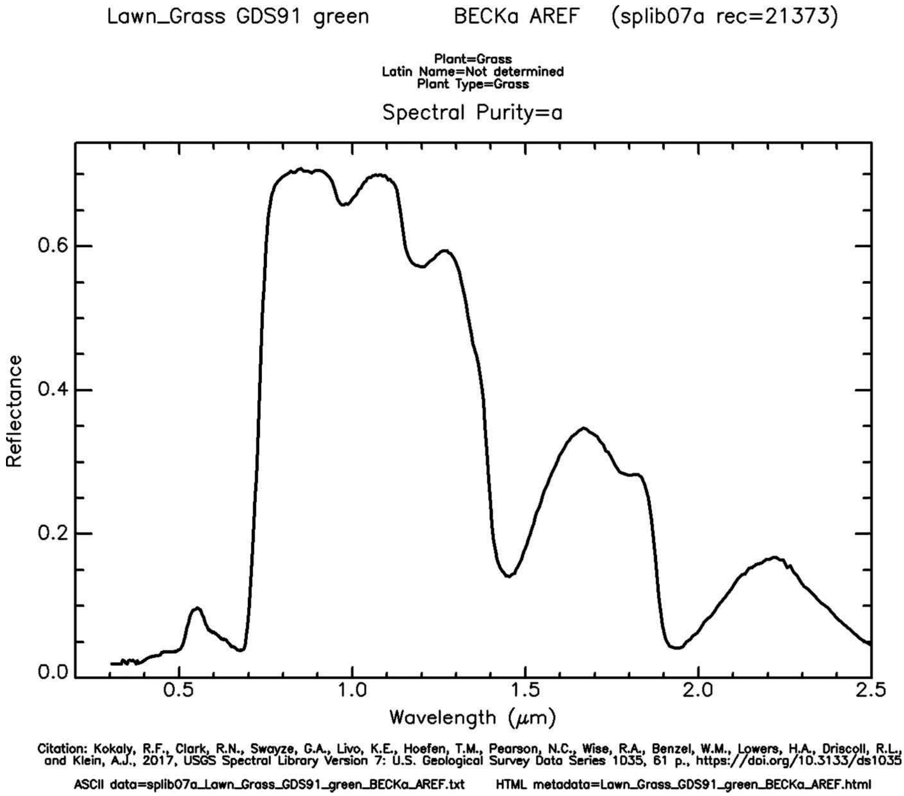

FIGURE 9.6
Spectrograph of healthy lawn grass (Kokaly et al., 2017) probably Kentucky bluegrass, from the lawn outside the USGS Spectral Library.

After reflectance has occurred the EMR must then pass back through the atmosphere (Figure 9.3d) where it is subjected to selective scattering and absorption once again. It may be detected and recorded by analog or digital sensors (e.g., cameras, scanners) operating on platforms in the atmosphere (e.g., UAVs, airplanes, helicopters), or it may pass out of the atmosphere and into low-earth space where sensors on orbiting spacecraft can record and transmit digital image data to ground receiving stations through a global network of geostationary communications satellites (Figure 9.3e). In the case of low-altitude UAVs the atmospheric effects after reflection are minimal. For higher altitude aircraft and satellites these effects are added to those from the incoming path of the EMR. All of this (from sun to sensor) takes place at or near the speed of light (approximately 300,000,000 meters/second). Concurrently, thermal IR sensors may detect longer wavelength thermal energy (heat) from earth surface features as well.

After EMR is sensed by a digital device (either fixed-frame, high-resolution digital cameras or line scanners of various types) it may be split into many bands or channels, and defined by a typically narrow wavelength range of the electromagnetic spectrum. Each of these channels (which can also be described as colors) are typically arranged in a raster data geometry and processed as high-precision georeferenced layers. The instantaneous field of view (IFOV) of line scanners (a solid angle) defines the pixel size that relates to the resolution of the image, typically given as the ground length width or height of a pixel. Imaging devices typically define and select channels between the wavelengths of 0.4 and 2.5 micrometers (μm). These values are sometimes given as nanometers (nm) such as 400–2500 nm. Wavelength ranges for multispectral channels are defined by the purpose of a particular sensor and the available windows in the atmosphere for sensing. Sensors comprised of several discrete channels (with spectral gaps between them) are termed multispectral. Those that record data across all or part of the normal range (e.g., 0.4–2.5 μm) using a large number of very narrow continuous channels are referred to as Hyperspectral Imaging Systems. These are becoming more commonly used, on platforms from UAVs to polar orbiting satellites, with hundreds of continuous, narrow-band channels.

After image data has been collected, with raw values recorded for reflectivity for each pixel in each channel, these values are then typically quantized to 8- or 16-bit positive integer values (Figure 9.3f). In the case of Landsat, 8-bit integers were used as per-pixel digital numbers (DNs) from 1972 until 2013. The 4-channel multispectral scanners on Landsat 1–3 thus produced 32-bit per pixel data through the 1970s. With the Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM) scanners on Landsat 4, 5, and 7 the six-channel combination (channels 1–5, 7) produced 48-bit per pixel data—astronomically more dense than MSS data. With the launch of Landsat 8 in February 2013, image data was quantized to 16-bit positive integers. The seven multispectral channels (1–7) produce 112-bits per pixel, covering nearly the entire earth with 30 meter pixels every 16 days. The consistent and well-documented data policies of this landmark program have made it even more valuable as it passes 40+ years of (near) continuous global coverage, data thickness, and (when brought into the GIS constellation) proven analytical power. Perhaps most importantly, nearly the entire catalog of multispectral data since 1972 is in the public domain and available at no cost through US Geological Survey portals such as GloVis (https://glovis.usgs.gov/) and EarthExplorer (https://earthexplorer.usgs.gov/).

The next step in the remote sensing process is a robust combination of fieldwork and analysis (Figure 9.3g). In best-case scenarios fieldwork is integrated through the entire remote sensing process. It precedes analysis, may be conducted during or concurrent with analytical work, and normally follows analysis. The types of field studies that may accompany remote sensing studies are as varied as the industries, services, and academic disciplines that use remote sensing technologies in their work. Professionals across the physical sciences (e.g., biology, chemistry, forestry, geology, geography, agronomy, pedology, hydrology, environmental science, etc.) employ remote sensing technology as a regular component of their basic and applied research. Remote sensing analysis has become a central component of many environmental analyses, and it is now commonly incorporated at several stages of work. In diverse engineering fields, LiDAR technology has become a key part of site selection and analysis, augmenting analytical and automated photogrammetry as important geotechnical services. In particular, transportation engineering has benefitted from the absolute precision and georeferencing inherent in LiDAR data services and products. Industries that are highly reliant on remote sensing services include the oil and gas, mining, forestry, and commercial agriculture sectors. In addition, numerous government agencies use remote sensing products and services. These include the US Geological Survey (USGS), National Oceanic and Atmospheric Administration (NOAA), National Weather Service (NWS), US Department of Agriculture (USDA), Environmental Protection Agency (EPA), National Aeronautics and Space Administration (NASA), Bureau of Land Management (BLM), Federal Emergency Management Agency (FEMA), and many more.

9.2 Organizational Considerations When Beginning Remote Sensing Work

When considering analytical remote sensing in any organization there are several questions that should be considered, as follows (along with comments to help guide answers):

1. *Do we need to acquire new technology to conduct remote sensing analyses?*
   The answer to this will usually be "no." If you have an up-to-date desktop computer this should suffice as a hardware platform for your work. Software is much less a problem than in the past. If you use ArcGIS or other commercial GIS you will likely already have the tools you need. ESRI, for example, has been adding remote sensing functionality over the past several major versions. There are also numerous low-cost or free software options available to meet the needs of most users for relatively sophisticated analytical work such as quantum GIS (QGIS), Multispec, GRASS GIS, and others.
2. *Do we need to hire new staff with specialized skills in remote sensing analysis?*
   The answer to this question depends on the size of your organization and perhaps the disciplinary diversity of your workforce. If you are part of a small organization and need remote sensing analysis you may not have employees skilled in the techniques and technology

needed for this work and will need to determine whether it is cost effective to develop these skills inhouse or outscource the work to service firms that specialize in these types of analysis. Most larger organizations (i.e., work with this data) have skilled staff with at least training in remote sensing courses and/or project experience with remote sensing data, image processing systems, and related applications. In this case you can work with HR to identify possible staff members for these types of projects for providing these skills and services internally. It may be the case that these capabilities already exist and are a regularly accessed functional component of your organization. These two questions can lead to another more complicated one:

3. *What types of analysis will we be able to do?*
   Introductory remote sensing courses normally build skills that focus on *two big questions*. The first question, what (and where) is it, suggests the use of different kinds of techniques for automated identification of particular types of land cover, features, or even objects in digital remotely sensed imagery. Image classification aims to drastically reduce the number of possible values in individual pixels of multispectral imagery to a manageable and useful set of classes. For example, Landsat 8 OLI data contains at least 112 bits of reflectance data in the first seven multispectral channels, producing an astronomical number of possible values in each pixel. Using image classification techniques we try to reduce that enormous number to a much more manageable set of categories with descriptive names, such as "forest," "agriculture," "urban – high density," and so on. We may also want to extract a small set of special values from an image, perhaps focusing on plant health, water or land temperature, or the presence or absence of vegetation. The second big question addressed in remote sensing is when (and how) something occurred. In this case, we often have to go outside our disciplinary boundaries to understand how something has occurred, in effect developing an understanding of specific processes by referencing other physical and human disciplines. For example, using remote sensing we may be able to determine that a flood has occurred and even the precise extent and volume of the flood through georeferencing and photogrammetry. We may even be able to determine with some precision when the flood occurred within the constraints of the temporal resolution of a specific sensor system. This is normally done by a process of image differencing, where an analyst subtracts georeferenced digital images of the same area (normally the older image from the newer) using the same channel (from the same range of the electromagnetic spectrum) but from different dates. This produces a difference image where pixels in the image that have not changed will be near zero, and pixels that have

increased substantially or decreased substantially will be near the tails of the difference image histogram. This technique can be effective for isolating reflectance changes over large areas for particular types of land-cover change analysis. To understand how or why a flood has occurred in a particular place and time, for example, we may need to use data from other disciplines such as climatology, meteorology, and hydrology.

Finally the remote sensing process that began at the sun (Figure 9.3a) ends with an analyst or team of analysts producing a set of knowledge products (Figure 9.3h) from their analysis of remotely sensed data and other peripheral geospatial and numerical datasets. This may include digital imagery or interactive web images as well as cartographic maps and thematic visualizations. Written reports link together all of this into a coherent and convincing response to a client's requirements.

9.3 Major Land Remote Sensing Projects

Since the inception of aerial photography and its incorporation into cartography and mapping allowed the relatively rapid and inexpensive mapping of much of the world during the 20th century, it should be no surprise that the incorporation of computing and digital imaging into this realm has created many new and useful geospatial information products. While the beginning of human space travel in the 1960s and the development of meteorological satellites first caused wonder and amazement, it very quickly resulted in determined activity to develop ways to create and use imagery from space for surveillance, environmental analysis, monitoring urban growth, and many other utilitarian applications. This reaction was not unlike the response to photographic images collected using early cameras from the gondolas of balloons over Paris by the Frenchman Nadar (Gaspard-Félix Tournachon) during the 1850s (Figure 9.7). The following section will discuss some of the major remote sensing projects, principally from the United States, that have shaped the terrain of civilian remote sensing today.

9.3.1 Government Aerial Photography

Following World War I, many government agencies began to experiment and use aerial photography for map compilation and other tasks related to natural resource and land management. This included federal agencies such as the USGS, US Department of Agriculture, and US Army Corps of Engineers. Many state agencies and other organizations operating at the

FIGURE 9.7
Nadar Élevant la Photographie à la Hauteur de l'Art, Daumier; Honoré-Victorin Daumier, lithograph on newsprint, *Le Boulevard*, 25 May 1862, currently in the collection of The Brooklyn Museum. Public-domain faithful reproduction of 2D artwork.

state and local levels also became active users of aerial photography for a number of purposes.

The USGS was perhaps the most active user of camera and film aerial photography in the period between the wars, compiling a 7.5-minute quadrangle map for the first time using aerial photography and photogrammetry in 1925. Through co-op programs with each of the states they regularly photographed the entire country as part of the program to complete 1:24000 scale topographic maps of the United States. Much of the photography that was used in this program, dating generally from the 1940s, is available online as single-frame high-resolution TIF files through a number of portals, most easily through EarthExplorer (see Figure 9.8). Although not generally well georeferenced at this time (2018), these images are invaluable resources for historical studies of urban change and development, and with minimal work they can be geospatially referenced and imported into project geodatabases. There are also many other aerial image products available through the EarthExplorer portal. Images from the last

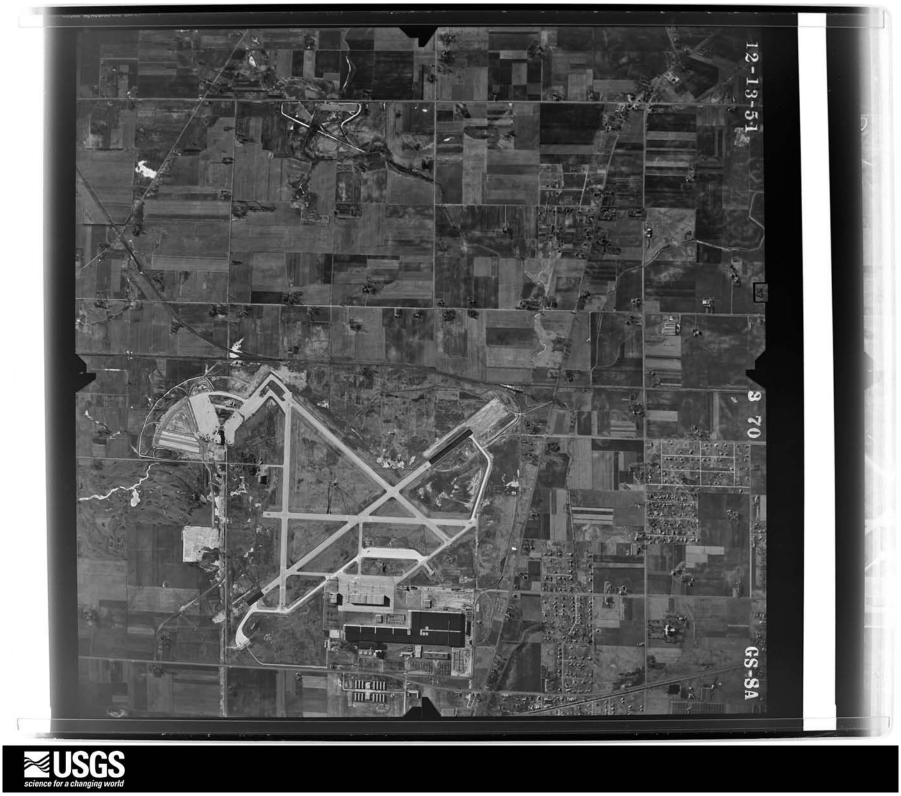

FIGURE 9.8
US Geological Survey Aerial Mapping Photograph, December 13, 1951, 1:23,600 scale, B/W film. At the time, Orchard Field, which was later renamed O'Hare Field, had no commercial flights and served as an Air Force base. Within 10 years, it would be the busiest airport in the world.

15 years are tightly georeferenced, high-resolution, four-channel digital images. The EarthExplorer interface is intuitively designed for exploration and discovery—dive in!

The USDA has also been a very active producer and user of aerial photography over the same period as the USGS. For decades these images were stored and provided to different parts of the agency and other related agencies from the Aerial Photography Field Office (APFO) in Salt Lake City. While the USGS tends to prefer leaf-off photography where available for easy viewing of cultural features in leafy cities, the USDA prefers leaf-on photography for viewing agricultural and natural resource features. The USDA, in cooperation with the Natural Resources Conservation Service (NRCS), offers a rich collection of raster and vector datasets through the Geospatial Data Gateway (https://gdg.sc.egov.usda.gov/) again with a relatively intuitive UI. This portal includes links to other rich resources of geospatial data such as

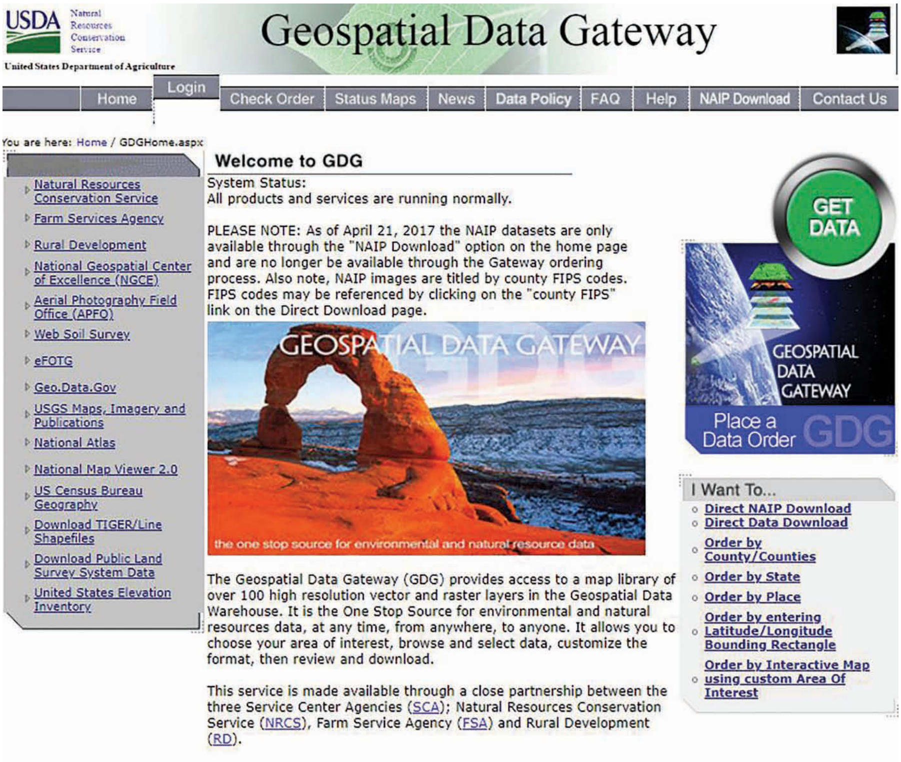

FIGURE 9.9
Geospatial Data Gateway, Natural Resources Conservation Service, USDA.

the US Interagency Elevation Inventory (https://coast.noaa.gov/inventory/) from NOAA, a great source for LiDAR and bathymetric datasets. The USGS GIS data site is also an extraordinary resource for many project-specific datasets not easily available elsewhere (https://www.usgs.gov/products/maps/gis-data; Figure 9.9).

Many state agencies are also notable producers and providers of public-domain aerial imagery, much of it in very usable digital formats. In Illinois, the Illinois State Geological Survey at the University of Illinois Urbana-Champaign provides a large collection of historical aerial imagery projects through the Illinois Geospatial Data Clearinghouse (http://clearinghouse.isgs.illinois.edu/; Figure 9.10).

One of these projects, completed between 1936 and 1941, was the first complete aerial imaging of the state of Illinois, acquired by the USDA for agricultural mapping. The original negatives of this project, including over 33,000 prints, were destroyed at the National Archives during the 1970s, most likely due to deterioration and instability of these materials.

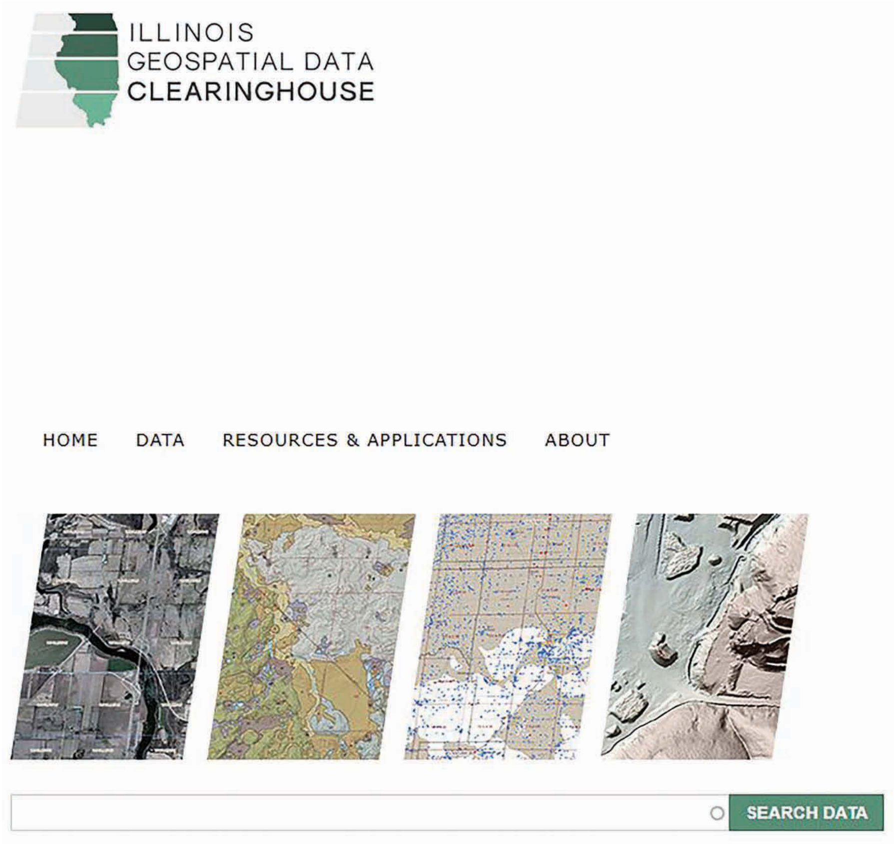

FIGURE 9.10
Illinois Geospatial Data Clearinghouse, Illinois State Geological Survey, University of Illinois.

Only two complete copies of contact paper prints of these negatives existed at the Illinois State Library and the University of Illinois Map and Geography Library. Partial or regional copies of portions of the complete collection exist in several county libraries and local government agencies. The images were scanned during 2001–2008 using original prints from these collections to produce a full collection of digital images covering the state. They have yet to be georeferenced. These priceless images, and an additional collection covering the Mississippi River channel, flown in 1927 following the Mississippi flood of that year, exemplify the importance of digital archives for these types of cartographic and remote sensing materials. Examples of their georeferenced and annotated use in the Google Earth browser can be seen at http://gis.depaul.edu/geography/webmapping/ (Figures 9.11 and 9.12).

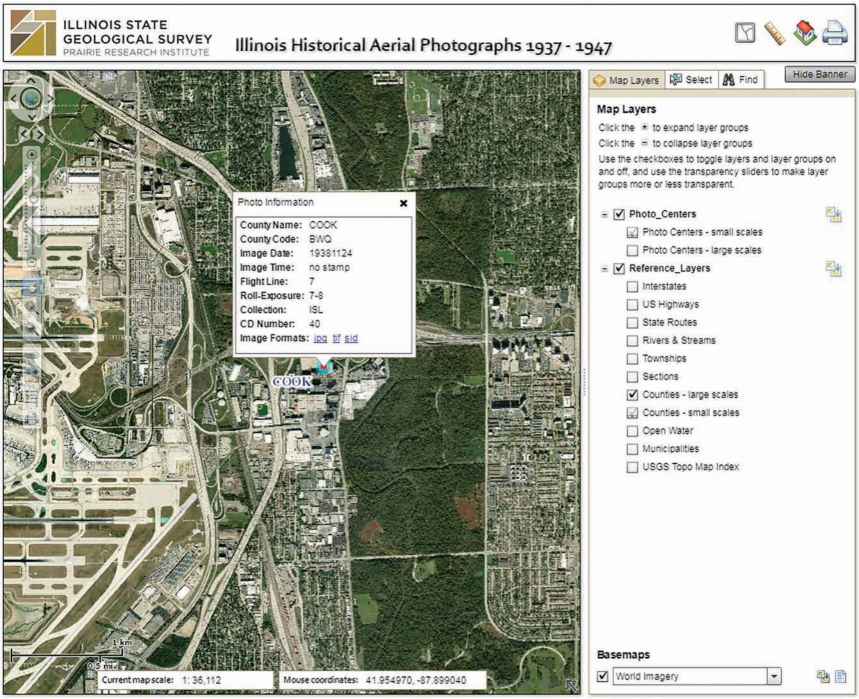

FIGURE 9.11
Illinois Geospatial Data Clearinghouse, Illinois State Geological Survey, Illinois Historical Photographs, 1937–1947.

9.3.2 Landsat and Other Multispectral Imaging Programs

What was later to become the Landsat program (originally dubbed the Earth Resource Technology Satellite, or ERTS) was conceived in the 1960s as an early response to the perception of environmental degradation and crisis, a civilian satellite focused on the Earth. Beginning in 1972 repetitive coverage of nearly the entire Earth by a medium-resolution, digital imaging satellite became a reality (initially every 18 days, but after the launch of Landsat 4 in 1982 every 16 days). This program has continued with only slight interruption to the present day, and in the age of the Internet under current US public-domain data policy, the entire catalog of Landsat imagery is available through several portals that allow contextual and geographically referenced searches for easy access. This archive is arguably the most important dataset in existence to document the onset and progression of global change in what many have dubbed the Anthropocene epoch.

During the 40+ years of operation through seven satellites and multiple sensors, the technologies for multispectral imaging in the program have changed substantially. There are three main categories of multispectral sensors that have been used (Table 9.1).

FIGURE 9.12
Historical Aerial Photograph, Schiller Park, Illinois, November 24, 1938.

TABLE 9.1
Landsat Satellites: Multispectral Sensors

Satellite(s)	Sensor	Approximate Dates	Comments
Landsat 1–3	Multi Spectral Scanner (MSS)	1972–1983	For data continuity the MSS was also part of the Landsat 4 and 5 system, but it was quickly superseded by the higher spectral and spatial-resolution TM. Some data from these sensors is available in the EarthExplorer archive.
Landsat 4, 5, and 7	Thematic Mapper (TM – L4 and L5) or Enhanced Thematic Mapper (ETM+ – L7)	1982–present (2018)	The Landsat 7 ETM+ sensor operated nominally until May 2003 when the failure of a scanning component degraded the data collected by the sensor. It is still marginally operational in 2018.
Landsat 8	Operational Land Imager (OLI) and Thermal Infrared Scanner (TIRS)	2013–present (2018)	The OLI–TIRS sensor system has moved civilian remote sensing into a new era with more spectral channels, improved image calibration and pre-processing procedures, and other system enhancements.

Detailed documentation of all aspects of the Landsat program are readily available online (https://landsat.usgs.gov/landsat-7-data-users-handbook). Another useful tool, the USGS Spectral Characteristics Viewer, is found at https://landsat.usgs.gov/spectral-characteristics-viewer.

Other nations have also joined in collecting and disseminating remotely sensed imagery since at least the 1980s, most notably France with the SPOT (Satellite Pour l'Observation de la Terre) satellite series beginning in the 1980s, and more recently the European Space Agency with the Sentinel remote sensing platform. The Sentinel project (https://lta.cr.usgs.gov/sentinel_2) is very similar to Landsat (and in some ways superior), with 10-meter resolution (visible and near IR), 5-day repetitive coverage, and 13 spectral channels. Imagery dated from 2015 to present is now available to remote sensing analysts through the EarthExplorer portal. India, Japan, and China have also become participants in the internationalization of civilian space remote sensing. Virtually all of these programs have followed the Landsat model, with some variation, using a raster data model for the storage and processing of images, resulting in discrete multispectral imagery in the visible and reflected IR spectrum, and (perhaps most exciting for geospatial analysts) georeferencing imagery available on the web. Many private firms such as DigitalGlobe, provider of much of the high-resolution imagery used in Google Earth and other Internet mapping platforms, are joining to meet the rapidly growing global demand for high spatial- and temporal-resolution imagery.

Over the past decade UAVs, commonly known as drones, have become an important and relatively inexpensive component of the remote sensing constellation. Autonomous aerial vehicles have a long history dating back to the early 20th century. Contemporary UAVs typically consist of small autonomous aerial vehicles, either fixed-wing or mini-helicopters, with a remote controlling wireless system and human operator. These devices may have different degrees of autonomous flight capability, and can be programmed to follow precise paths using onboard GNSS and perform imaging functions automatically. With the wide availability of many different types of inexpensive miniaturized sensors, and their ability to operate at very low elevations, UAVs have become an inexpensive way to collect high-resolution imagery. In the United States this explosion of largely unregulated civilian aircraft has resulted in governmental response, placing restrictions on where flight can occur, limits on elevations of UAVs, and the qualifications and training necessary to operate these devices. Of course, most of the restrictions relate to airports (Figure 9.13). At the time of writing, regulations regarding the operation of UAVs are fluid and locally specific. For example, Chicago airspace is regulated by federal, state, local, and even university regulations regarding UAV operation. Those considering using these devices as remote sensing platforms should always review and abide by all applicable regulations for their location.

FIGURE 9.13
Photo by Author, sign along Highway A1A, Patrick AFB, Satellite Beach, Florida, June 17, 2018.

9.4 Digital Remote Sensing Data

The wide availability of sensors, computing systems, and platforms coupled with the need to integrate these products into an array of programming and development environments has resulted in a diverse landscape of remote sensing data types and formats. The following is an overview of some of the most commonly used.

9.4.1 Sensors

Commonly divided into active and passive categories, virtually all sensors operate by recording reflected or emitted electromagnetic radiation, normally within specific wavelength ranges. They range in size from large electronic systems with several modules weighing hundreds of kilograms to small micro-sized devices with low power requirements that easily mount on small- to medium-sized UAVs. They almost always structure their data as fixed-line length raster arrays. A notable exception to this are active lidar scanners where raw data is structured as point-vector 3D layers.

Table 9.2 gives the typologies of some common sensors currently in wide use. Due to the rapid development of miniaturization in digital cameras and

TABLE 9.2

Sensor Types and Data Characteristics

Digital Sensor Type	Resolution	Wavelength Sensitivity/Channels	Common File Types	Comments
Full-frame aerial camera	Rapidly changing, currently 2.5 cm ground resolution is fairly common. Public domain historical imagery (scans from analog images) and digital full-frame camera orthoimages can be acquired through EarthExplorer (https://earthexplorer.usgs.gov/).	4-channel imaging common, visible blue (0.4–0.5 μm) green (0.5–0.6 μm) red (0.6–0.7 μm) and Near IR (0.7–1.1 μm)	GeoTIFF, HDF, ArcGRID	These are commonly used on aerial platforms operating in the atmosphere at elevations ranging from very low (tens of meters) to very high (up to 15,000 meters). Because resolution (ground pixel size) is dependent on platform elevation, these are often used for producing orthophotos (georeferenced aerial images) as the final product.
Multispectral cross-track scanner	Common spaceborne medium resolutions range from 10 to 30 meters with frequent revisits. UAV applications can produce extremely high resolution (as fine as 1 cm) with low altitude scans. Multispectral scanner data in the public domain at various resolutions can be acquired from EarthExplorer (https://earthexplorer.usgs.gov/) or GloVis (https://glovis.usgs.gov/).	Medium resolution commonly acquire seven to ten channels across the visible, and near to mid (reflected) IR (0.4–2.5 μm). Lightweight UAV multispectral scanners may have up to five discrete channels in the visible and near IR.	GeoTIFF, HDF, IMG	While discrete multispectral scanners have long been associated with well-known polar orbiting land remote sensing satellites (e.g., Landsat, SPOT, Sentinel) these types of sensors are now being used on UAV platforms much more commonly.
Thermal imaging scanner	Lower resolution (60–100 m) than multispectral sensors in spaceborne land remote sensing satellites. Public-domain thermal imagery from the Landsat Program (1984–present) can be acquired from EarthExplorer (https://earthexplorer.usgs.gov/) or GloVis (https://glovis.usgs.gov/).	Thermal IR ranges are approximately 8–15 μm, but the Landsat satellites with thermal channels have taken advantage of the 10.5–12.5 μm range in particular.	GeoTIFF, HDF	Many meteorological satellites have thermal IR scanning capabilities, but since they are generally intended for sea surface temperature studies the resolution of these sensors (e.g., GOES, MODIS) have historically been rather coarse. Since the 1980s the Landsat Thematic Mapper and now the TIRS sensor on Landsat 8 have provided medium-resolution thermal IR sensing that has given much greater detail of thermal features on land and in near-coastal areas.

(*Continued*)

TABLE 9.2 (***Continued***)

Sensor Types and Data Characteristics

Digital Sensor Type	Resolution	Wavelength Sensitivity/Channels	Common File Types	Comments
Hyperspectral scanner	Can range from 1 cm scale on UAV-mounted systems to 30 m on spaceborne systems such as Hyperion, an experimental sensor on the EO-1 satellite. Hyperion data can be acquired through EarthExplorer (https://earthexplorer.usgs.gov/).	Typical maximum spectral range covers 0.3–2.5 µm using hundreds of channels. Some sensors, particularly those on UAV platforms, cover smaller subsets of this range.	GeoTIFF	Hyperspectral sensors produce a continuous set of values for each pixel across a wide range of the visible and IR spectrum. Each channel covers a very narrow spectral range, normally 2-15 nm, producing hundreds of separate channels. Because this requires much more data to be processed simultaneously, the number of pixels across a single track will normally be substantially less than typical multispectral scanners.
LiDAR (light radar)	Raw lidar data is collected and stored as vector data, fundamentally points with three (x, y, and z) ordinate values in reference to an earth model. Public-domain lidar data for a growing number of sites are available through EarthExplorer (https://earthexplorer.usgs.gov/).	As an active topographic sensor, lidar uses pulses from visible and near IR lasers, measuring the time of their reflected return using the speed of light. Normally sensing in the near IR, precisely positioned sensors generate a point cloud of classifiable 3D data.	LAS, LAZ	Lidar has rapidly become a technology driving innovation in diverse fields such as archaeology, GIS and surveying, geology, hydrography, etc. Operating from UAV platforms, low-cost LiDAR sensors allow production of relatively inexpensive, precise, and rapid digital elevation models (DEM).
Radar	Shuttle Radar Topography Mission (SRTM) data (February 2000) can be acquired at 1-arc second (approximately 30 m) resolution for 80% of Earth's land area. Available through GloVis (https://glovis.usgs.gov/).	An active sensor, the Shuttle c-band radar collected interferometric data in the 5.8 cm microwave range. In ranges used for topographic mapping the advantage of cloud penetration has made radar imagery highly desirable for use in tropical regions.	GeoTIFF	The SRTM mission was conducted on a shuttle flight in 2000. The radar equipment had been previously flown on two shuttle missions in 1994. It was modified for the 2000 mission to collect return signals using two separate antennas on the shuttle, allowing high-resolution elevation data to be acquired for land areas between 60° north and 56° south.

increasing widespread availability of UAV platforms, this is a dynamic area of sensor integration with GNSS and application development. The capabilities and sizes of the cameras used in aerial sensing have changed rapidly over the past decade and include greater sensitivity and precision in spectral discrimination and much finer resolution. Resolution is typically given as a linear ground-distance measurement of one side of a single pixel. Wavelength values or ranges are given in micrometers or centimeters (microwaves). Filetypes referenced in Table 9.2 for specific sensors are those commonly used in the systems discussed.

9.5 Remote Sensing Applications

When used in GIS, remote sensing is often used to answer the two questions discussed in section 9.3.3. The first question is relatively simple, but because the subjects of GIS and geography are so complex (encompassing the world and everything in it) answering it can be quite involved.

- What (and where) is it?

In remote sensing this question would most likely be answered using some form of image classification, either unsupervised or supervised. In unsupervised classification an analyst determines the number of desired classes and using the ISO Cluster routine (ArcGIS Desktop 10.5, ISO Cluster Unsupervised Classification) operating on a multispectral image composite across visible and IR channels completes an iterative grouping, placing each pixel into the class it most closely resembles based on reflectance values recorded for that pixel. Field work then establishes the most likely identity of each class of pixels.

Supervised classification starts with the analyst creating small training samples, vector polygons that outline small areas of land cover to be identified. Statistics from each of the multispectral channels in an image composite are collected using the training sample polygons and used to establish a "spectral signature" for each training sample. Using any number of different classification algorithms, these signatures are then compared to each pixel and each pixel is then categorized into one of the classes derived from the training sample. These classified images can then be used to analyze land cover. The "where" part to the question is answered by the tightly georeferenced imagery being used in the context of GIS. The resulting classified images are georeferenced using the same parameters as its parent images.

The second big question follows almost intuitively:

- When (and perhaps why) was it located there?

The when question can often be answered by performing image differencing change analysis. This technique is used more generally to establish widespread changes that have occurred in an image area between any two points in time for which we have good multispectral imagery. Another possible resource for exploratory work on the "when" question is the Google Timelapse project (https://earthengine.google.com/timelapse/). There are a number of prerequisites to performing this type of analysis:

- Tightly georeferenced raster imagery from two dates
- Completely cloud free (or as much so as possible)
- Imagery from the same channel or same spectral range
- Imagery with the same bit depth (8- or 16-bit normal)

Precise georeferencing ensures that pixels covering a particular feature or area in one image covers the same area in an image from a different date. Cloud-free images ensure that clouds (that will be detected as an area of great change) do not bias or corrupt the analysis. Imagery from the same channel or spectral range ensures that we are comparing reflectance in the same part of the spectrum in both images. The most common problem in performing this analysis with Landsat imagery regarding bit depth occurs when using Landsat 8 and previous Landsat data. Landsat 8 sensors collect data using a 16-bit integer (65,536 possible values), while previous Landsat satellites recorded reflectance data using an 8-bit integer (256 possible values). We normally down-convert Landsat 8 data to 8-bit integers before performing image differencing with data from an earlier Landsat multispectral sensor.

After performing a simple radiometric correction to account for different sun elevations at different times of the year, we apply image differencing onto appropriate single-channel images. The outcome of this calculation is a difference image. When viewing the histogram of this image we can see that the form of the histogram is near normal and that the mean of the image data is relatively near zero. The closer to zero the mean of the image is gives us some idea of how successful our radiometric correction has been. The tails of the histogram are areas in the image that have changed substantially between the two dates, and those we are most interested in. If we subtracted the older image from the newer image, the highest values from the difference image would be the pixels that have become substantially brighter. Areas that have become substantially darker will be in the left or negative tail of the histogram. These values can then be classified either manually or using some other logic (Figure 9.14).

It is also possible to link together two or more change analyses to compare rates of change in a particular area over longer periods of time (see Figure 9.15). For purposes of comparison, the analyst should determine the number of days between successive images and then normalize the

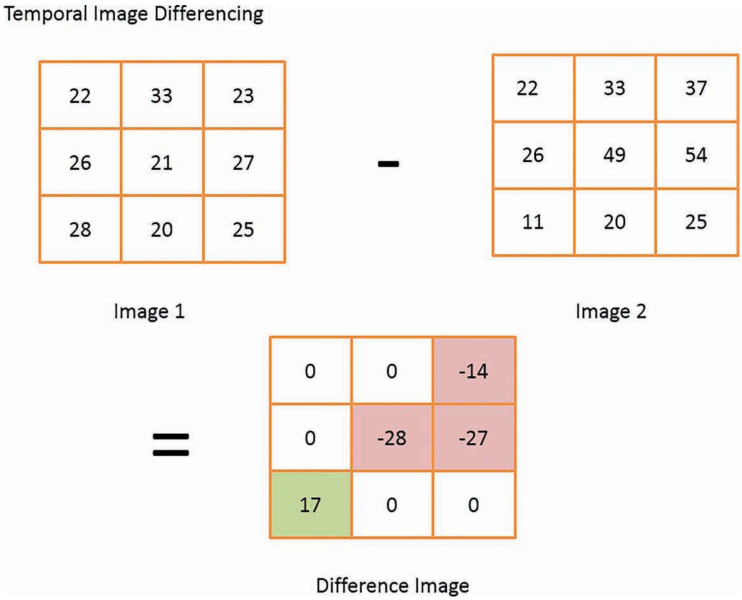

FIGURE 9.14
Temporal image differencing using Raster calculator. Image 1 (newer) – Image 2 (older) produces a difference image where 0 values are no change, significantly positive values are substantially brighter and significantly negative values are substantially darker.

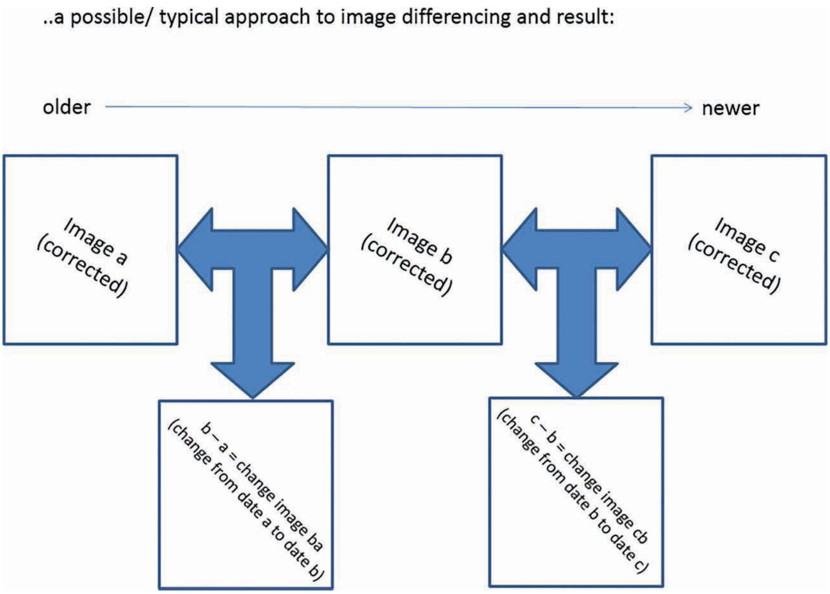

FIGURE 9.15
Sequencing temporal change analyses.