Applications of Remote Sensing for Lake Basin Management

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Introduction

Remote sensing is the use of a sensor to measure characteristics of an object without physically touching the object. While this description may sound artificial and unfamiliar, we are in fact all intimately familiar with process of remote sensing. Each person is a walking, taking, breathing compilation of remote sensors.

We use our eyes to see our world by capturing and interpreting the visible light that reflects off trees, dogs, cars and pavement.

We use our nose to smell our environment by sensing chemicals in the air which were released by garbage, flowers and freshly baked bread.

We use our ears to convert pressure waves into sound, allowing us to hear a distant bird call, a crying baby and music played on a piano.

As exemplified by the number of ways in which we experience our surroundings using our own senses, remote sensing as a science is characterized by a wide range of techniques, equipment and applications. Remote sensing is utilized in an amazingly diverse set of arenas, including disaster management, agriculture, community development, natural resources, transportation, military, and invasive species.

The focus of this section is to describe the use of remote sensing in the context of lake management. By the end of this chapter, you will become familiar with:

1. Basic Remote Sensing Concepts and Terminology
2. Characteristics of Remote Sensors
3. Examples of Remote Sensing in Lake Management
4. Important Considerations When Selecting a Remote Sensor

Basic Remote Sensing Concepts and Terminology

Remote sensing devices are used throughout the world to measure an incredibly diverse set of environmental features, including wave heights, bathymetry, topography, water quality, land cover and surface temperature. Remote sensors accomplish these varied tasks by recording the intensity of light, or other types of electromagnetic radiation, which are emitted or reflected from the objects which the sensor is designed to measure (trees, water, elevation, etc.). While the entire spectrum of electromagnetic radiation covers energies ranging from gamma rays to radio waves, most remote sensors used in natural resource applications rely on the visible and infrared wavelengths (0.4 μm to 4.6 μm), as well as, thermal wavelengths (6.5 μm to 14.5 μm). These wavelengths represent the portion of the spectrum that interacts in a measurable and predictable manner with features of interest on the Earth, such as water bodies, trees, wetlands and paved surfaces. By monitoring the variations in intensity and spatial patterns of these wavelengths, remote sensors provide a mechanism for tracking environmental change on our planet.

All remote sensors measure radiation which reflects off of or is emitted from an object of interest. Remote sensors fall into two broad categories based on the way in which they interact with the features they are measuring. The majority of sensors, known as passive sensors, rely on the sun to provide the electromagnetic radiation which illuminates the objects of interest. These sensors can only be used during daylight hours, and due to the types of radiation they typically measure (visible, infrared, thermal), can be interfered with by environmental conditions such as clouds and haze. On the other hand, active sensors produce their own radiation with which objects can be measured. These sensors can be used with equal effectiveness regardless of the time of day, and due to the types of wavelengths on which they rely (sonar, radar), are less hampered by environmental conditions. The vast majority of sensors used to monitor lakes and watersheds are passive sensors.

When referring to specific remote sensors, it is fairly easy to get confused by the list of names associated with each device. It is important to realize that most remote sensors are referred to with two different names depending on the context: (1) the name of the sensor itself and (2) the name of the platform on which the sensor is carried. The most common platform for remote sensor is the satellite, but remote sensing devices can also be carried on aircraft, mounted on blimps, hung from balloons or even carried by hand.

The realization that the sensor and platform names are linked, but separate entities is crucial when having a conversation about remote sensing. For example, NASA's Landsat 7 satellite carries the Enhanced Thematic Mapper (ETM) sensor. When people refer to Landsat data, they are referring in fact to data collected by the ETM sensor carried on the Landsat 7 satellite. This distinction is even more important when multiple sensors are carried on the same platform. In another example, NASA's Terra satellite carries a multitude of sensors, two of which are widely used (ASTER and MODIS) by the water remote sensing community.

Characteristics of Remote Sensors

Most remote sensors are designed with a specific application in mind. For example, NASA's Thematic Mapper (TM) sensor was designed to study long term changes in land cover, while NASA's MODIS sensor was developed to monitor frequent changes in oceanic conditions. When deciding which sensor to use for lake monitoring, many questions could and should be asked. Several of these questions are:

- In what ways do TM and MODIS differ fundamentally?
- Can TM be used to monitor water quality, in spite of being designed to measure changes in land cover?
- Can MODIS be used to monitor lakes, in spite of being constructed to measure oceanic water quality trends?

In order to understand the differences in the vast array of remote sensing options and evaluate the potential usefulness of each sensor for a particular application, it is important to understand some of the terminology that describes remote sensors. The following paragraphs will cover several fundamental characteristics of remote sensors and discuss the importance of each to better prepare the reader for informed discussion of remote sensing options.

Spatial Resolution

Description

The spatial resolution of a sensor describes the size of a pixel in the imagery produced by that sensor. The size of an image pixel in a sensor is the result of a range of design factors, including the type of lens radiation light for the sensor to measure, the number of pixels on the sensor itself, the elevation above the ground from which the sensor captures images, the angle of view of the sensor, etc. The size of pixels on publicly accessible satellite remote sensor's range from as large as a 1.1 km to less than 1 meter.

Importance

Pixel size is very important factor in determining the size and types of features visible in an image. Images with large pixels can reveal landscape size features over a large area, but will not have enough fine detail to document smaller features. In the case of small lakes or lakes with a convoluted shoreline, large pixels can leave out many of the most interesting sections of the water body. On the other hand, while images with small pixels allow for the observation of small water body features, these images are often data dense and have smaller footprints. Images with smaller pixels could provide too much data to handle, or might not cover the entire water body when working with a larger lake system.

Footprint (Extent)

Description

The footprint of a sensor describes the size of a single image provided from that sensor. In some cases, the footprint represents a single image acquisition from the sensor (such as a snapshot would be). In many cases, the footprint size is somewhat artificial. Satellites that collect data continuously often have data broken into individual images for data distribution, in which case the image footprint is imposed after the data has been collected. Also, some imagery can be purchased by sections of a single image, as opposed to the entire image footprint. Some sensors, especially aircraft-borne sensors, do not have their data broken into image tiles. Instead, the imagery from these sensors instead are distributed as a swath, which appears as a stripe of imagery running along the Earth.

In all of the cases described above, the size of an image from a remote sensor can be described by a combination of the swath length (image size in the direction of sensor travel) and swath width (image size perpendicular to the direction of sensor travel). Swath width is related to the spatial resolution of the sensor because most sensors have a similar number of pixels per image. While there is not a one-to-one relationship between pixel size and swath width due to variations in sensor and platform design, there is a central maxim which is rarely violated: smaller image pixels result in a smaller swath width, while larger image pixels result in a larger swath width.

Importance

The footprint of a sensor determines the amount of area which can be observed with a single image. The swath width of remotely sensed imagery can vary from a few hundred meters to thousands on kilometers, while the swath length can vary to a similar degree. If you are trying to observe fine details over a small area, a sensor with a small footprint might be appropriate. However, if observations are desired over a large area, a choice would have to be made between the acquisition many images with small footprints (and most likely smaller pixels) or fewer images with large footprints (and most likely larger pixels).

Temporal Resolution

Description

Temporal resolution describes how often a remote sensor has the chance to capture an image of the same place on the Earth, a length of time often referred to as revisit time. Most satellite sensors simply record data from the area directly below the sensor, or at nadir. In this case of nadir-looking sensors, the swath width determines the repeat time. The wider the swath width, the less time it takes for the swath width to "repaint" the same spot on the earth. Some satellites have the ability to tilt or point the sensor, providing the ability to capture images of the same spot on the Earth more often than would be possible with a fixed sensor. The off-center views produced when the satellites are tilted to capture imagery from locations not directly beneath the satellite are known as non-nadir. While the ability to capture non-nadir imagery can be seen as an advantage, these sensors do not capture a continuous record of the areas over which they are flying (unlike nadir sensors), and thus do not provide a global catalog of imagery.

Aircraft-borne sensors are in a completely different category when it comes to temporal resolution. Unlike satellites airplanes are not constantly in flight and can not provide global imagery catalogs. The temporal resolution of an individual aircraft sensor is difficult to predict, since a wide variety of factors need to be considered (distance from aircraft origin of the study site, local weather conditions, competing aircraft usage, etc.). In general, aircraft-borne sensors have great temporal resolution in the short term, and poor temporal resolution in the long term.

Importance

The frequency with which the images of an area can be obtained, and the number of images of a water body that can captured over time, has an enormous impact on the potential applications of a particular sensor. Satellite sensors with revisit times from one to several days can be used for tracking environmental changes (such a water quality) on a weekly basis, allowing detailed observation of ecosystem dynamics over time. Sensors with revisit times closer to two weeks provide information on system dynamics over a broader times scale, such as monthly or seasonal. Aircraft-borne sensors are difficult to use for long term studies, due to the difficulty in obtaining repeated images of the same area over time. However, the benefit of aircraft sensors in lay in the ability to finely control the time of day at which images are captured, something which satellite-borne sensors are unable to accomplish.

Spectral Resolution

Description

Spectral resolution describes the width, number and position of the "bands" a remote sensor uses to measure incoming radiation. Unlike laboratory spectrophotometers than capture spectral continuous spectral information at increments of ~1 nm, most remote sensors measure radiation at discrete areas of the spectrum based on the spectral characteristics of the features which the sensor is designed to measure. Some multispectral sensors have only four bands or segments of the spectrum over which data are collected, while others measure radiation at over 30 wavelength ranges. Hyperspectral sensors have vastly more areas of measurement (often 200+ bands), and provide continuous spectral data approximating laboratory equipment.

Importance

The number, position and width of bands present in a sensor have an enormous influence on the applications for which a sensor can be used. While a few sensors have the ability to adjust bands on the fly, the vast majority of remote sensors have unmovable bands which are chosen based on the application for which the sensor was designed. For the measurement of land features (as in the case of Landsat ETM), wide bands in the visible and infrared range provide sufficient information for many applications. For the observation of in-water features (as in the case of MODIS), sensors with narrow bands strategically placed in the visible portion of the spectrum are best suited. While hyperspectral sensors are rare in satellites, the continuous spectral measurements they provide allow for ultimate application versatility. Due to the detailed spectral data they provide, and resultant ability to mimic the bands of any other sensor, hyperspectral sensors are often deployed on boats or in aircraft as a part of the process of algorithm development in water bodies.

Radiometric Resolution

Description

Radiometric resolution refers to sensitivity with which a sensor can measure changes in the intensity of radiation. This type of resolution in measured in "bits", which refers to the range of numbers by which radiation intensity is measured by the sensor. For example, an 8-bit sensor has a minimum value of 0 and a maximum value of 255 (28 = 256). An 8 bit sensor would measure the darkest pixel in the world as 0, and the brightest as 255, leaving 256 possible levels of intensity for each individual measurement. A 12 bit sensor would have a maximum value of 4095 (2^{12} = 4096), allowing for over 15 times as many levels of intensity as an 8 bit sensor.

Importance

The higher radiometric resolution a sensor possesses, the finer detail with which it can measure changes in radiation intensity. Higher radiometric resolution is most important when measuring features which do not reflect radiation in large quantities, such as areas in shadow on the land and water bodies such as lakes are rivers. In the case of surface water, typically less than 10% of incoming light at a given band would be reflected from the sun to the sensor. As a result, an 8-bit sensor would have a range of only 0-25 to represent all possible variations in signal from water bodies, while a 12-bit sensor would have over 12 times the sensitivity to changes in light intensity over water (range of 0-409).

A good analogy for different levels of radiometric resolution in remote sensors is the task of making measurements of the height of a tomato plant with three different meter sticks. Meter stick number 1 would be marked with decimeters only, stick number 2 would marked only with centimeters, and the final meter stick would have millimeter markings. The ability to accurately measure small changes in size would be much greater with the stick number 3, because the increased "radiometric resolution" would allow for the measurement of smaller increments of variation than either stick 1 or stick 2. In the case of these meter sticks, a crude estimate would have to be made between the decimeter and centimeter markings, resulting in a lack of sensitivity to small increments of growth, and a likely under or overestimation of plant size.

The Use of Remote Sensing in Lake Management

Remote sensing has been used increasingly in lake management over the past fifteen years, but is still far behind land remote sensing and ocean remote sensing in adoption and overall public awareness. The three case studies described below provide powerful examples of the potential use of remote sensing to monitor lake water quality.

Describing long-term trends of water transparency in Minnesota (USA)

The University of Minnesota's Remote Sensing and Geospatial Analysis Laboratory and Water Resource center has worked for nearly a decade to implement remote sensing based monitoring of water clarity trends for thousands of lakes in Minnesota. The success of the program is due to the collaboration of research scientists at the University and numerous volunteer lake monitoring groups throughout the state. The University researchers provide the technical skill necessary to obtain and process satellite imagery, while the volunteer monitors provide Secchi disk data with which to calibrate the satellite images. The majority of the satellite imagery used in this project has been Landsat TM and Landsat ETM, which has limited the lake size to larger than 20 acres (although lakes as low as 10 acres can be measured with these sensors). Additional satellite imagery was acquired from IKONOS to provide the finer spatial resolution necessary in urban areas.

The results of the project to date have been nothing short of spectacular. The University researchers have coupled data from ~850 volunteer-monitored lakes with satellite imagery to produce maps detailing Secchi disk depth of over 10,500 lakes, over 12 times as many lakes than were monitored by traditional sampling along. The project has produced water clarity maps for Minnesota lakes in 1990, 1995, 2000 and 2005. While each date is useful for measuring spatial trends of water quality, the multiple dates of imagery have allowed for long term trend monitoring in the lakes of the state. The research group at the university has already worked with the nearby states of Wisconsin and Michigan to implement their technique, and is continuing to work with other states and organizations to provide the foundation for satellite based monitoring of long term water quality trends.

To see an example of their satellite derived lake water quality data in action, visit the Minnesota LakeBrowser at http://water.umn.edu/lakebrows.html.

For more information in a journal article:
Brezonik, P.L., L.G. Olmanson, M.E. Bauer, and S.M. Kloiber. 2007. Measuring Water Clarity and Quality in Minnesota Lakes and Rivers: A Census-Based Approach

Table 1: Common satellite sensors used for lake and watershed monitoring applications.
Titles in italics indicate the category of sensor characteristic described in each column.

				Global	*Spectral*		*Spatial*	*Footprint*	*Temporal*	*Radiometric*
Sensor	**Satellite**	**Agency**	**Launch**	**Coverage**	**Bands**	**Blue**	**Pixel Size (m)**	**Swath (km)**	**Revisit (d)**	**Intensity Levels**
—	QuickBird	Digital Globe Inc.	2001	NO	5	YES	0.7, 2.8	16.5	1-3.5*	11-bit (0-2047)
—	IKONOS	GeoEye	1999	NO	5	YES	1*, 4*	13.8*	3-5*	11-bit (0-2047)
—	SPOT 5	CNES (France)	2002	NO	6	NO	2.5, 10, 20	60	2-3*	11-bit (0-2047)
ASTER	Terra	NASA (USA)	2002	YES	15	NO	15, 30, 90	60	16	8-bit (0-255)
Hyperion	EO-1	NASA (USA)	2000	NO	220	YES	30	7.5	16	12-bit (0-4095)
TM	Landsat 5	NASA (USA)	1984	YES	7	YES	30, 80	60	16	8-bit (0-255)
ETM	Landsat 7	USGS (USA)	1999	YES	8	YES	10, 30, 60	185	16	8-bit (0-255)
CZI	HY-1B	CNSA(China)	2007	YES	4	YES	250	500	7	10-bit (0-1023)
MERIS	ENVISAT	ESA (Europe)	2002	YES	15	YES	300	1150	3	16-bit (0-65535)
OCM	IRS-P4	IRSO (India)	1999	YES	8	YES	350	1420	2	12-bit (0-4095)
MODIS	Aqua	NASA (USA)	2002	YES	36	YES	250, 500, 1000	2330	1.5	12-bit (0-4095)
COCTS	HY-1B	CNSA(China)	2007	YES	10	YES	1100	1400	1	10-bit (0-1023)
AVHRR/3	NOAA-18	NOAA (USA)	2005	YES	6	NO	1100	3000	1	12-bit (0-4095)
SeaWiFS	OrbView-3	NASA (USA)	1997	YES	8	YES	1100	2801	1	10-bit (0-1023)

**figures represent off-nadir values.*

Using Remote-Sensing Techniques. CURA Reporter 37: 3-13.

Online at http://water.umn.edu/Documents/Brezonik_et_al-Measuring_Water_Clarity.pdf

Monitoring reservoirs in Spain for potentially-toxic cyanobacteria

The majority of surface water bodies in Spain are reservoirs, many of which are experiencing a shift in dominance to potentially toxic cyanobacteria. As a national agency charged with monitoring all of Spain's reservoirs, the Center for Public Works Study and Experimentation (CEDEX) located in Madrid found itself in desperate need of a technique to repeatedly survey a large number of reservoirs. The goal of the project was to produce a system with which to detect reservoirs undergoing cyanobacterial blooms at any point in time, allowing for reservoir managers to respond in a timely manner to the potential danger these blooms represent.

The first step in the development of the remote sensing technique was to characterize the spectral patterns of Spanish reservoirs, and relate those patterns to cyanobacterial concentrations. From 2001 to 2007 CEDEX collected limnological and boat-based remote sensing measurements from 65 reservoirs located throughout the country. The results from the reservoir sampling were used to test an cyanobacteria algorithm developed for the MERIS sensor on the ENVISAT satellite by a team from Vrije Universiteit in Amsterdam. The satellite algorithm from the Dutch research team proved useful in Spanish reservoirs, allowing for the development of a cyanobacterial monitoring and assessment systems for reservoirs throughout Spain.

For more information in a journal article:
Simis, S.G.H., A. Ruiz-Verdú, J.A. Domínguez-Gómez, R. Peña-Martinez, S.W.M. Peters, and H.J. Gons. 2007. Influence of phytoplankton pigment composition on remote sensing of cyanobacterial biomass. Remote Sensing of Environment 106: 414-427.

Measuring chlorophyll distribution in Lake Grada (Italy)

Lake Grada is the largest lake in Italy, and as such, provides on of the biggest challenges for lake monitoring and management in this country. Chlorophyll measurement from a satellite sensor seem to be an ideal method for monitoring such a large lake. An experimental remote sensor, Hyperion carried on the EO-1 satellite, was found to provide the spectral, spatial and radiometric resolution necessary for the task. However, Hyperion has rarely been tested for use in lake water quality monitoring.

To test the utility of Hyperion for chlorophyll monitoring in Lake Grada, researchers from the Optical Remote Sensing Group (Italy) teamed up researchers from the Environmental Remote Sensing Group (Australia) and Uppsala University (Sweden). The team used on-lake remote sensing measurements to produce a chlorophyll algorithm, with was applied to Hyperion imagery to produce a chlorophyll map of the lake. The chlorophyll values from the imagery were compared to in situ data collected during the Hyperion overpass, which was collected with spot sampling techniques and by continuous flow-through systems. The chlorophyll concentrations derived from the imagery exhibited a strong correlation with the field collected chlorophyll samples, providing strong evidence that a hyperspectral satellite sensor could be used to monitor Lake Grada and other subalpine lakes.

For more information in a journal article:
Giardino, C., V.E. Brando, A.G. Dekker, N. Strombec and G. Candiani . 2007. Assessment of water quality in Lake Garda (Italy) using Hyperion. Remote Sensing of Environment 109: 183-195.

Important Considerations When Selecting a Remote Sensor

When choosing a remote sensor for use in lake management, it is important to consider the needs of your application and the characteristics of the body (or bodies) of water to be measured. Some of the questions you should consider are:

- Would you like to observe in-water features, or land features surrounding the lake?
- How large is the lake would like to observe?
- What types of measurements would you like to make?
- How often do you need measurements to be taken?
- How much expertise is required to handle/analyze the imagery?
- How much does the imagery cost?

Would you like to observe in-water features, or land features surrounding the lake?

If you would like to observe in-water features, such as water clarity or chlorophyll, it is important to make sure that the sensor has a band in the blue portion of the spectrum (see Table 1). Blue light penetrates water much deeper than either green, red or infrared light, and as such, is invaluable for sensing changes in phytoplankton or water constituents. Blue bands are also useful for viewing land features as well, as it allows for clearer distinction between shadows and surface water. However, plenty of land cover and land use data development has been accomplished with sensors without blue bands.

How large is the lake would like to observe?

The size of the lake or feature of the lake (bay, inlet, etc.) will play an enormous role in the selection of the appropriate sensor. For large lakes or large land areas, sensors designed for the open ocean with 1-1.1 km pixels (such as AVHRR/3, COCTS SeaWiFS, MODIS) will provide sufficient spatial resolution. For lakes too small for such large pixels, another option would be the medium resolution sensors, such as CZI, MERIS and OCM. The pixels in these sensors (250-350 meters) are still too big for a many lakes, but they might prove useful in lakes where having 9-16 pixels for every 1 km pixel from the ocean sensors would produce useable data on water characteristics. Satellite sensors such as ASTER, Hyperion, TM and ETM can provide fairly detailed land mapping and are useful in lakes down to ~4 hectares in size. Fine resolution sensors such as SPOT, IKONOS and QuickBird would provide very fine details of both land and water bodies (keeping in mind that only SPOT has a blue band), but it is possible that the small footprint of these sensors may not cover a large enough area to be useful for some applications.

What types of measurements would you like to make?

Most of the sensors mentioned in this report would be useful to measure simple water quality and landscape characteristics, but only a handful of the sensors have bands designed to study in-water characteristics. For example, Landsat TM and ETM have been used successfully to monitor lake water clarity, but have proved more difficult to use in the detection of chlorophyll. Most satellite sensors designed for ocean remote sensing (COCTS, CZI, MODIS, MERIS, SeaWiFS) have bands strategically positioned to measure chlorophyll concentrations in water. The only sensor, however, which has a band which can be used to distinguish between cyanobacterial pigment absorption and typical chlorophyll absorption in MERIS (Hyperperion, due to its hyperspectral nature, can also measure this difference in absorption).

How often do you need measurements to be taken?

It is very important to keep in mind that you will not get a clear image (cloud free) of your water body or land area each time the satellite passes over your study area! The numbers discussed below are best case scenarios, and should be evaluated in that context. Certainly the less time between each pass, the more often you will get imagery. However, do not believe that a 1-day revisit time translates into an image of your lake every day. It is possible that the sensor could provide a clear image for eight days in a row, then have a spell of clouds or other environmental conditions that prevent a useable image from being capture for the next ten days.

In general, the large pixel sensors have much larger swaths, which results in lower revisit times. The sensors with 1 km pixles (AVHRR/3, COCTS, SeaWiFS) have revisit times ranging from 1-2 days, the medium pixel sensors (CZI, MERIS, OCM) have revisit times ranging from 2-7 days and the smaller resolution sensors (ASTER, ETM, TM). Hyperion has a 16 day revisit time, but due to it's small swath, does not provide global coverage and may not collect data over your area of interested on each pass. The satellites which can be tasked have a hypothetical revisit time of 1-5 days, but it is important to keep in mind that there are a variety of factors which influence when and were images are taken by these sensors (including weather, priority and amount of cost involved in competing tasks for a given day).

How much expertise is required to handle/analyze the imagery?

The amount of expertise required to handle remotely sensed imagery varies widely from sensor to sensor, as does the ease with which you can procure the imagery. Some sensors, such as MODIS can be downloaded through a data portal online and can be manipulated with free software provided by NASA. Other imagery, such as MERIS, can be analyzed with free software (provided by ESA), but is much more difficult to download. Hyperspectral data is the most difficult to handle (Hyperion) due to the enormous number of bands which are part of the imagery data set. In general, the commercial satellite sensors (IKONOS, QuickBird, SPOT) provide data which is the easiest to use in typical mapping software, but this ease of use can be contingent on the amount of cost associated with each image. All remotely sensed imagery can be analyzed to some extent using commercial Geographic Information Systems (GIS) software, and to a large extent with image processing software (ERDAS Imagine, ITT ENVI). Free software does exist for handling most types of remote sensed imagery, but training and experience is needed to do advanced analysis.

Several options for free imagery viewers can be found here:

- BEAM - http://141.4.215.13/
- Mulitspec - http://cobweb.ecn.purdue.edu/~biehl/MultiSpec/
- SeaDAS - http://oceancolor.gsfc.nasa.gov/seadas/
- ViewFinder - http://www.umac.org/agriculture/tutorials/1/info.html

How much does the imagery cost?

In the cases of some imagery, this is an easy question to answer; in the cases of imagery from other sensors, the answer is very complex. In general, the imagery produced by commercial sensors (IKONOS, QuickBird, SPOT) will be much more expensive than other imagery types, and will have a layered fee structure depending on the accuracy and details of your contract. Also, commercial imagery products are licensed, which means that the money you paid for the imagery provides you with the right to use the imagery in any way you see fit, but does not provide you with the right to share that imagery with others. Some types of imagery, such as MERIS and MODIS are freely available, although the ESA does put some restrictions on the free access to MERIS imagery. Other NASA data products are in the price range of several hundred dollars (Landsat TM and ETM) to one thousand dollars per image (Hyperion), but the licensing situation is much less restrictive. As such, it is possible to find images freely available from organizations which have already purchased the data from NASA. Satellite data from China and India can sometimes be obtained directly from the agency which controls that satellite, but is sometimes available through commercial resellers (who set their own prices).

Relevant Reference Information

International Institute for Geo-Information Science and Earth Observation satellite and sensor database
Online at: http://www.itc.nl/research/products/sensordb/searchsat.aspx

International Ocean Colour Coordinating Group ocean color sensor page
Online at: http://www.ioccg.org/sensors_ioccg.html

Jensen, John R., 2007, *Remote Sensing of the Environment: An Earth Resource Perspective,* 2nd Ed., Upper Saddle River, NJ: Prentice Hall, 592 pp.

Manual for Monitoring European Lakes Using Remote Sensing Techniques. 1999. EUR 18665, ISBN 92-828-5390. Environmenta and quality life series. Eds. Tommy Lindell, Donald Pierson, Guido Premazzi, Eugenio Zilioli. Luxembourg: Office for Official Publications of the European Communities. 164 pp.

Olmanson, L.G., Kloiber, S.M., Bauer, M.E., and Brezonik, P.L. 2001. Image processing protocol for regional assessments of lake water quality. Water Resources Center and Remote Sensing Laboratory, University of Minnesota, St. Paul, MN, 55108, October 2001.
Online at: http://resac.gis.umn.edu/water/regional_water_clarity/content/form.html

Remote Sensing for Coastal Managers from United States National Oceanic and Atmospheric Administration Coatal Services Center:
Online at: http://www.csc.noaa.gov/crs/rs_apps/