6. Remote sensing and GIS integration

A.M. Dean (Hatfield Consultants Partnership, North Vancouver, Canada) and J. Populus (IFREMER, Plouzané, France)

6.1 INTRODUCTION

As described in Chapter 1, the majority of the problems currently faced by world fisheries lie in the spatial domain, and fisheries and aquaculture management challenges extend over large geographic areas, including inland areas, coastal zones and open oceans. As a result, remote sensing (from fixed coastal locations, aircraft and satellites) has been used to provide a large range of observation data to support fisheries and aquaculture management, which complement and extend data acquired from in situ observations. Satellite remote sensing in particular provides a unique capability for regular, repeated observations of the entire globe or specific regions at different spatial scales. There is unprecedented availability of global and regional oceanographic and terrestrial remote sensing data and derived information products, which can meet many of the needs of fisheries and aquaculture managers. Much of the useful data and information are directly derived from satellite remote sensing[161], but in many cases remote sensing data are integrated with in situ and other spatial data.

This chapter introduces the basics of remote sensing and its main applications to support fisheries and aquaculture management. There often appears to be an overwhelming number of remote sensing data options and sources; therefore, an aim is to provide practical guidance for planning and implementing the use of remote sensing, including data selection and acquisition, image processing and the integration of images with GIS. While remote sensing is often viewed only as a source of input data for GIS, remote sensing data can also be integrated into Web-based or desktop applications that are not GIS in the traditional sense, such as Google Earth or decision-support systems. This chapter also illustrates four case studies, which provide an overview of how remote sensing has been applied to support coastal aquaculture mapping and sensitive habitat mapping, monitoring development of potentially harmful ocean conditions, and the identification of potential fishing grounds.

6.2 THE BACKGROUND TO REMOTE SENSING

Remote sensing is defined as “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, Kiefer and Chipman, 2007; p. 1). Usually, the devices are sensors mounted on satellites or aircraft, or are installed at fixed coastal locations, that measure the electromagnetic radiation (EMR) that is emitted or reflected by features of the earth’s surface, and which then convert the EMR into a signal that can be recorded and displayed as either numerical data or as an image. There are numerous introductory texts on remote sensing and image processing, which provide comprehensive information on concepts and foundations and specific applications (see Section 6.7 below) and an extensive glossary of remote sensing is available at www.ldeo.columbia.edu/res/fac/rsvlab/glossary.html#S. The following subsections provide a basic overview of some important remote sensing concepts, including electromagnetic energy, remote sensing platforms plus their orbits and sensing systems, and a range of general characteristics about remote sensing.

[161] Though remotely sensed data from aircraft-based sensors may be important in certain situations.

6.2.1 Electromagnetic energy

The science of remote sensing is based on the physics of wave theory, which describes how electromagnetic energy takes the forms of waves (Rees, 2001). Sensors measure variations in the EMR emitted by or reflected from an object, area or phenomenon. EMR is classified into several types according to the wavelength or frequency of the wave, e.g. X-rays, visible light, infrared or microwaves. The full range of wavelengths of electromagnetic energy is often referred to as the electromagnetic spectrum and classes of wavelengths are often called spectral bands (see Table 6.1). Sensors will usually detect energy in more than one spectral band in a part of the electromagnetic spectrum and are therefore called multispectral sensors.

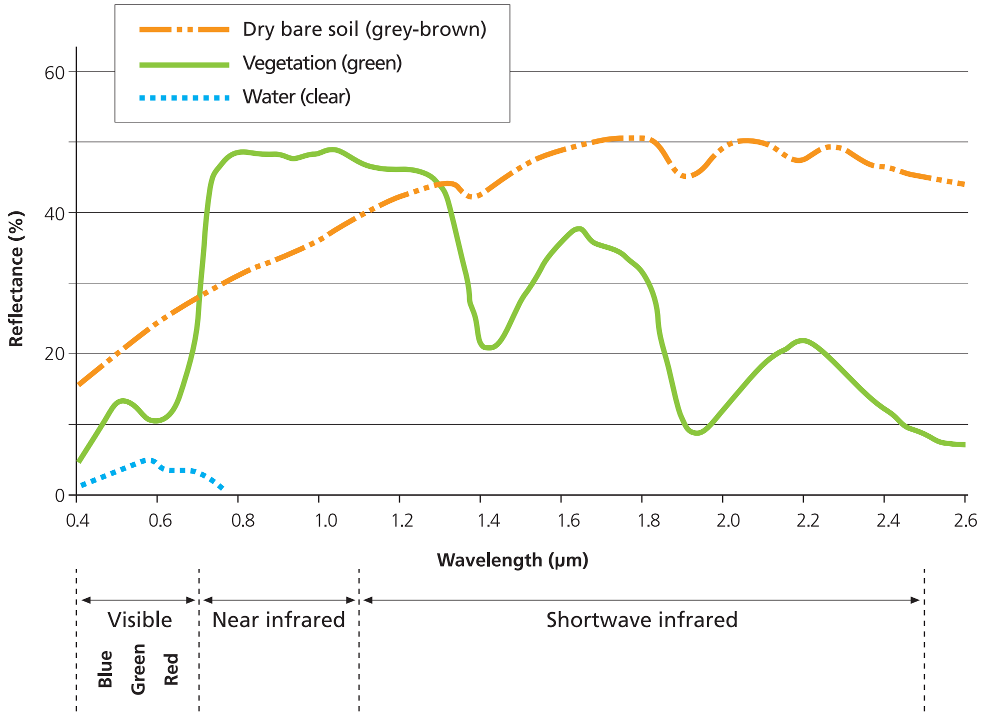
TABLE 6.1
Wavelengths and spectral bands of the electromagnetic spectrum of interest for fisheries and aquaculture applications

Spectral band or wavelength	Characteristics	Examples
Visible 0.4–0.7 µm	High atmospheric scattering effect. Most energy is reflected solar radiation and therefore only detected during the day. Penetrates water to a certain depth.	Natural colour photography and video.
Near infrared 0.7–3.0 µm	High reflectance by vegetation. Most energy is reflected solar radiation and therefore only detected during the day.	Black and white and colour photography, video camera, optical scanner.
Medium infrared 3.0–8.0 µm		Infrared photography, multispectral optical scanner.
Thermal 8.0–1 000 µm	Energy emitted by the earth and ocean surfaces and atmosphere.	Thermal imager or scanner.
Microwave 1 mm–100 cm	Energy emitted at low levels by the earth and ocean surfaces. Penetrates clouds and is possible to detect during the night. Possible to generate the microwave energy as part of an active remote sensing system, or detect emitted microwaves where the original source of energy was the sun.	Imaging radar, radar altimetry, high-frequency radar, Passive microwave radiometer.

In a remote sensing system, EMR that has been reflected or emitted from an object or area of the earth's surface is measured by a sensor. The source of the energy can be the sun (optical remote sensing) or a radar system that provides its own source of energy. Energy measured in the thermal band comes mainly from the sun's incident energy that has been absorbed by the object or area and re-emitted as thermal radiation.

Objects, areas and phenomena often reflect and emit energy in different parts of the electromagnetic spectrum in a predictable repeatable way; this is often called a "spectral signature" for optical remote sensing (visible and infrared wavelengths). The spectral signatures can be analysed to look for relationships and to determine useful information such as the vegetation type or water quality. Figure 6.1 gives the spectral signature of various natural terrestrial features. In imaging radar remote sensing, the term spectral signature is not commonly used because satellite radar systems usually only measure one wavelength or frequency.

FIGURE 6.1
Spectral signature of water, vegetation and soil surface features



Spectral signatures may vary with time (e.g. as plants grow and ocean productivity changes) and as the amount and angle of incident energy from the sun changes (e.g. with season or latitude); therefore, when analysing remotely sensed data it is important to consider the date and time of acquisition and the topography (for terrestrial applications).

6.2.2 Types of remote sensing systems

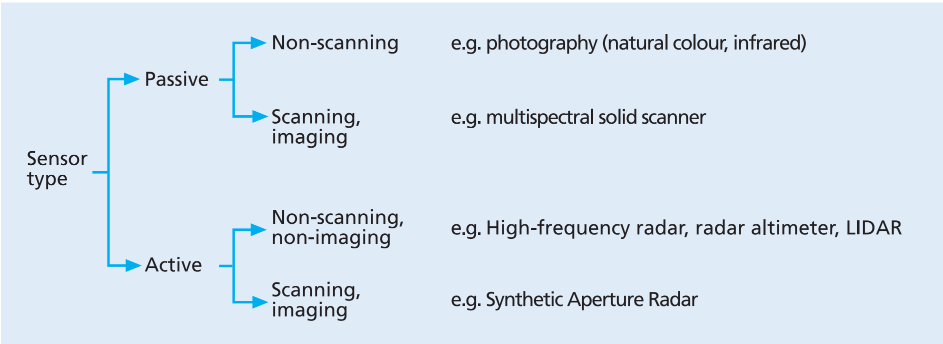
Remote sensing systems can be categorized based on many criteria, and a useful hierarchy is shown in Figure 6.2. First, there is the distinction between"active" and "passive" types of sensor – passive sensors only measure reflected EMR whereas active sensors emit their own sources of EMR and measure the response. Subsequently, there are "scanning" and "non-scanning" sensing systems. Scanning implies motion across the surface over a time interval, and non-scanning implies that the sensor is fixed on an area or target of interest as it is sensed. Finally, "imaging" and "non-imaging systems"are categorized, where the imaging systems build up a two-dimensional image of the surface and non-imaging sensors take measurements in one linear dimension.

The most relevant types of remote sensing systems for fisheries and aquaculture are:

- Multispectral optical – passive scanning systems that collect images (imaging) as the sensor passes or sweeps over the surface to build up an image.
- Camera photography – passive non-scanning system.
- Imaging radar – active scanning systems that illuminate objects or areas with their own source of microwave energy that is directed to the side and downwards to the earth's surface. It arrives at the surface at an angle and the backscattered energy is measured by the sensor to create an image. A synthetic aperture radar (SAR) is a special type of imaging radar and is a complex system that measures both the amplitude and phase of the return signals to create a high-resolution image (Travaglia *et al.*, 2004).

- Light detection and ranging (LIDAR) – active non-scanning system that is non-imaging. However, through data processing the data may be represented as an image, i.e. because the millions of point measurements can be processed to form a digital elevation model in raster-image format.
- Radar altimetry and high-frequency (HF) radar – active non-scanning and non-imaging systems that are used to measure sea surface height and currents.

FIGURE 6.2
Types of sensor

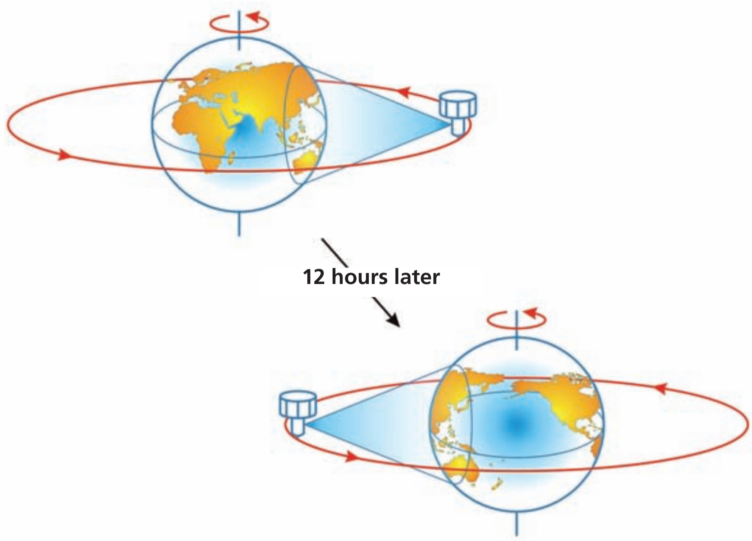


Source: Adapted from Harvey (2008).

6.2.3 Platforms and satellite orbits

A platform refers to the structure on which the sensor or multiple sensors are mounted. A platform is typically an aircraft or satellite, but platforms can also be established in fixed locations as is the case for coastal HF radar used for sea surface current monitoring. Satellites orbit the earth to provide repetitive coverage. The satellite altitude and orbit play an important part in the resolution or scale of the data that can be acquired and the revisit frequency; the main types of orbit are described in Box 6.1 and Figures 6.3 and 6.4. Satellite platforms provide repetitive coverage and an opportunity to build up long-time series of imagery, but they are not as flexible as airborne platforms in terms of scheduling acquisitions. Airborne platforms are usually fixed-wing aircraft flying at 400 to 3 000 m altitude, and modern optical digital cameras or radar systems can acquire imagery from these platforms at scales from 1:5 000 to 1:20 000 depending on the requirements of the user. Airborne systems can carry sophisticated sensors, for example, the hyperspectral Compact Airborne Spectrographic Imager (CASI) that provides a large number of adjustable spectral bands.

FIGURE 6.3
Geostationary satellite orbits



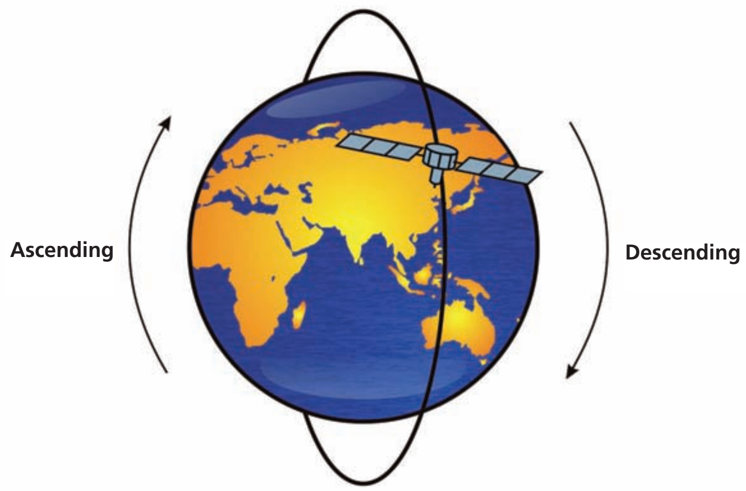
BOX 6.1
Satellite orbits

Satellite revolutions around the earth can be characterized under the two main headings: (i) geostationary and (ii) orbiting.

(i) Geostationary satellites operate from a geosynchronous orbit at approximately 35 900 km above the equator – at this altitude the speed of the satellite can exactly match the speed of the earth's rotation so they remain stationary above a specific point (Figure 6.3). This means that they can achieve a high observation frequency, but their spatial resolution has remained in the kilometre range so far. High latitudes regions are not well observed because of the oblique angle between the earth's surface and the satellite sensor. The main applications are communications and meteorology.

(ii) Orbiting satellites operate at altitudes between about 270 and 1 600 km and are usually polar orbiting and sun-synchronous, meaning that they have orbits that cross the north and south polar areas and that cross the equator at the same sun time each day. As a satellite revolves around the earth, the sensor "sees" a certain portion of the earth's surface. The width of the surface area imaged is referred to as the swath (see Canada Centre for Remote Sensing: www.ccrs.nrcan.gc.ca/resource/tutor/fundam/chapter2/02_e.php). There are a huge number of different orbiting satellites, some of which are designed for global mapping and have a very broad extent or swath (e.g. 500 to 2 000 km) and relatively coarse spatial resolution (300 m to 4 km). Other orbiting satellites carry sensors designed for more detailed mapping, which have smaller extents or swaths (e.g. 10 to 50 km), but can provide high spatial resolution data (e.g. 50 cm to 10 m). The satellite orbits as the earth rotates, which enables the sensors to build up global coverage; eventually, the satellite sensor observes the same point above the earth, which defines its revisit schedule. Change analysis using multitemporal data is one of the most useful aspects of remote sensing. Radar satellites have the ability to operate at night and can, therefore, acquire imagery as they orbit from north to south (descending) and from south to north (ascending) as shown in Figure 6.4.

FIGURE 6.4
Polar satellite orbits

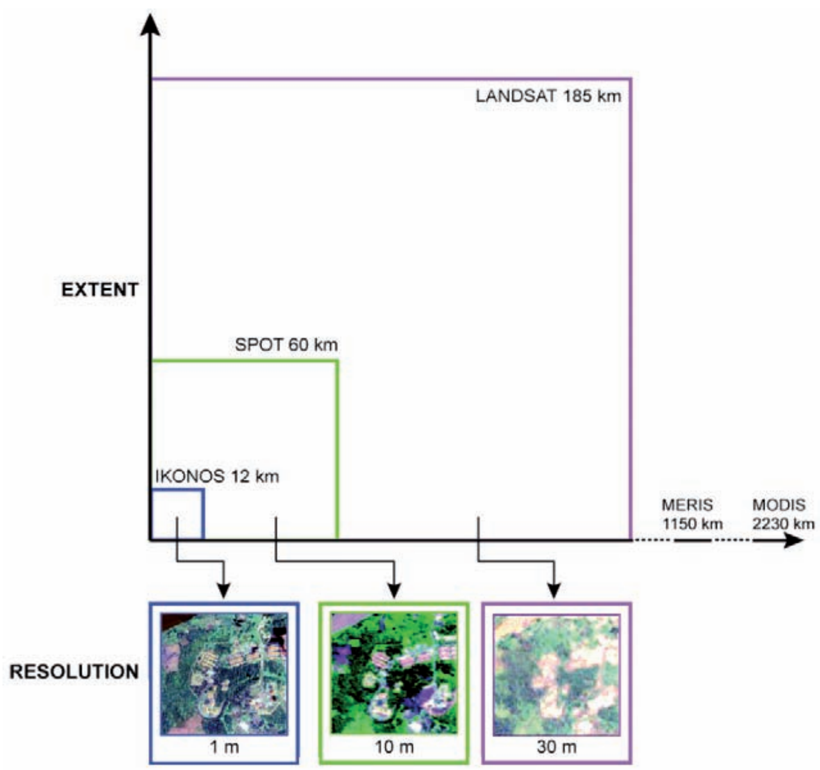


6.2.4 Characteristics of remote sensing systems

Sections 6.2.1 and 6.2.2 provide a very succinct background to the ways in which remote sensing operate as a complex data gathering system, and Figure 6.2 shows that there is a range of different sensors being utilized with numerous parameters being measured at different temporal and spatial resolutions. In order to "navigate" the available systems and their products, the user needs to consider the varied characteristics of the whole system:

- **Information content.** Defines what is being measured by the satellite sensor and/or what parameters are being derived using models and complementary in situ data. The number and precision of the "spectral bands", or wavelengths, over which the sensor operates is an important property – further information on this is provided in Section 6.2.1. The accuracy and precision of the measurements and the amount of processing already completed by the data provider are also important considerations.
- **Spatial extent.** Information derived from remote sensing can be global or cover only regional or local areas. Figure 6.5 shows the aerial extent of the scenes (or images) gathered by three of the main satellite systems. Depending on the remote sensing systems, there will be different properties, such as spatial resolution and revisit frequency for different spatial extents. Data and information acquired for global studies are typically less detailed (relatively coarse) compared with those acquired for specific areas.
- **Spatial resolution.** Remote sensing data are usually processed into an image format and it is sufficient to understand that spatial resolution is the size of the individual picture element (pixel) recorded by the sensor. Depending on the application, "low resolution" might be 30 m and "high resolution" might be 1 m, e.g. aquaculture pond mapping; or low resolution may be 20 km and

FIGURE 6.5
Overview of the spatial extent and resolution of selected types of remote sensing imagery



high resolution might be 4 km, e.g. sea surface temperature (SST).The spatial resolution has an important impact on the mapping scale of the product and whether the geographic patterns of interest can be described in enough detail for an application. Users often desire high-resolution satellite data, but for very large areas a compromise is often needed, i.e. as data may be too expensive to acquire and the volumes impractical to process.

- Revisit frequency. This defines the frequency that observations can be made of the same area, which for satellite remote sensing depends on the satellite orbit, extent and spatial resolution of the imagery. Cloud cover also affects the revisit potential of optical systems. While many sensors claim frequent revisit, their capacity to cover large areas may be limited. Some satellite sensors can "look" to the side of their orbit to provide more frequent coverage, but in most cases vertical observations are better for accurate, detailed mapping. Constellations of three or more of the same or compatible satellites can improve the revisit frequency.
- Time series. The time period for which consistent observations are available. Future continuity of data supply from a particular sensor, or a group of sensors with similar spatial and spectral resolutions, may be important to ensure that frequent, ongoing information will be available to support the user's information needs.
- Timeliness. The speed that a product is made available to a user. Real time and near real-time products are designed to be delivered as quickly as possible, often called "nowcast" by oceanographers. Historical time-series products can be developed over long periods and are delivered after careful compilation and calibration, which may be called "hindcast" by oceanographers and modellers. The capability for a product to be delivered in a very timely manner may also depend on the amount of processing that is required.
- Levels of processing. Many data suppliers refer to "data levels", which describe the amount of processing that the data supplier has conducted before the product is made available to the user. Data levels can be summarized as follows[162]:
  - Level 1A – unprocessed instrument data at full resolution.
  - Level 1B – instrument calibrations have been applied to Level 1A data to provide more consistent values
  - Level 2 – derived variables at the same resolution as the source Level 1 data, e.g. SST data, where the spatial resolution of the data may vary across the image;
  - Level 3 – derived variables in a regular grid formation, e.g. a regular grid of SST data. Level 3 data are sometimes called "binned" because they have a regular grid, or "mapped" if they have been map projected.

6.3 REMOTE SENSING OUTPUT OF USE TO FISHERIES OR AQUACULTURE GIS

Different types of remote sensing data are suitable for specific fisheries and aquaculture applications, and user requirements can vary considerably. For most fisheries and aquaculture applications, the main types of remote sensing data are categorized into optical imagery and radar, so these provide convenient headings to examine the information received from the sensors.

Box 6.2 summarizes the features and strengths of each type of remote sensing system; more information on the electromagnetic spectrum is provided in Section 6.2.1.

---

[162] Adapted from the National Aeronautics and Space Administration (NASA): http://oceancolor.gsfc.nasa.gov /PRODUCTS/product_level_desc.html.

BOX 6.2
Main types of optical and radar remote sensing systems

Optical: These images are intuitive to interpret, but cloud cover can limit their availability. Specifications and costs of data vary considerably.

- **Visible and infrared** – Sensors can provide land cover and land use information for inland fisheries applications, ocean condition data such as chlorophyll-a and suspended sediment concentration, bathymetry and sea surface temperature (SST), and data to support coastal zone fisheries and aquaculture management.
- **Light detection and ranging (LIDAR)** – An airborne system that can provide precise elevation data, usually for small areas. When combined with detailed visible and infrared optical imagery, this can be used for land cover and topography mapping, for example, in intertidal zones.

Radar: These systems are not affected by cloud cover, but radar data are less intuitive to interpret than optical imagery.

- **Imaging radar** – Images can contain unique information compared with optical images, such as the flooded status of vegetation or surface roughness of a waterbody, but it typically can determine fewer land cover classes than optical data.
- **Radar altimeter** – Can be processed to provide information on sea surface height, surface currents, waves and winds.

High-frequency radar: Installed in fixed locations along the coastline and provides data on surface currents and waves within a specific (localized) geographic area.

6.3.1 Optical remote sensing systems and products

Sea surface temperature

A summary of satellites and sensors relevant for sea surface temperature (SST) observations is provided in Table 6.2. Since the late 1970s, SST measurements have been operationally available from the Advanced Very High Resolution Radiometer (AVHRR) sensors on the National Oceanic and Atmospheric Administration (NOAA) and TIROS meteorological satellites. Other sensors include the National Aeronautics and Space Administration (NASA) Moderate Resolution Imaging Spectroradiometer (MODIS) sensors on board the Earth Observing System (EOS) Aqua and Terra satellites, and NOAA's Geostationary Orbiting Earth Satellites (GOES) that are geostationary over the Western Hemisphere (see Box 6.1). Section 6.5.2 on selecting and acquiring data provides some information on obtaining SST products from these satellites.

TABLE 6.2
Summary of SST-related optical remote sensing systems

Sensor	Satellite(s)	Operational period	Orbit/swath width	More information
AVHRR	NOAA 4 to 19 and TIROS METOP-A	1978 to present 2007 to present	Polar orbit 2 399 km swath Global coverage every day	www.oso.noaa.gov/poesstatus
MODIS	EOS TERRA EOS AQUA	1999 to present 2002 to present	Polar orbit 2 330 km swath Global coverage every one to two days	http://modis.gsfc.nasa.gov
Imager, Sounder	GOES 1 to 12	1975 to present	Geostationary orbit Western Hemisphere	http://goespoes.gsfc.nasa.gov/goes/project
ATSR AATSR	ERS-1 and 2 Envisat	1991 to present 2002 to present	500 km swath Global coverage every three days	http://envisat.esa.int/instruments/aatsr http://envisat.esa.int/handbooks/aatsr

Ocean colour

Ocean colour refers to obtaining information about the ocean using optical sensors, including parameters such as concentration of chlorophyll-*a*, which is a measure of primary productivity, and total suspended matter (TSM), which is related to turbidity. A summary of satellites and sensors related to ocean observations is provided in Table 6.3. No single ocean colour sensor is capable of observing every part of the globe every day, so a combination of sensors is often used. Following the successful launch in 1978 of the Coastal Zone Color Scanner (CZCS), there have been several overlapping ocean colour satellite missions. Currently, SeaWiFS, MODIS, Medium Resolution Imaging Spectrometer (MERIS) and others provide data to support operational oceanography products. There are also national missions, such as Oceansat-1 (India). The International Ocean Colour Coordinating Group (IOCCG) provides a good summary of the current and future availability of ocean colour sensors (IOCCG: www.ioccg.org/sensors_ioccg.html). Future sensors of particular interest are those on board the European Space Agency (ESA) Sentinel-3 (launch 2014) and NOAA's NPP and NPOESS (2011 and 2014). Section 6.5.2 provides some information on obtaining ocean colour products.

TABLE 6.3

Summary of ocean colour related optical remote sensing systems

Sensor	Satellite(s)	Operational period	Orbit/coverage
SeaWiFS	OrbView-2	1997 to present	Polar orbit, 1 500 km swath
MODIS	EOS Terra, EOS Aqua	1999 to present, 2002 to present	Polar orbit, 2 330 km swath, global coverage every one to two days
MERIS	Envisat	2002 to present	Polar orbit, 1 200 km swath
Ocean Colour Monitor (OCM) 1 and 2	Oceansat-1 and 2	1999 to present, 2009 to present	1 400 km swath, global coverage every one to two days

Source: International Ocean Colour Coordinating Group (www.ioccg.org/sensors_ioccg.html).

Inland and coastal zone mapping using optical sensors

There are many optical remote sensing systems suitable for mapping land cover, inland waterbodies and the coastal areas that are of interest for fisheries and aquaculture. Some of the sensors for SST and ocean colour mapping can also provide information for terrestrial mapping, although the spatial resolution of the sensors is usually considered to be too coarse. The main optical systems are shown in Table 6.4 and ESA's future Sentinel-2 satellite is described in Box 6.3.

TABLE 6.4

Summary of optical remote sensing systems relevant for inland and coastal zone mapping

Sensor	Satellite(s)	Operational period	Swath width, spatial resolution	More information
MSS	Landsat 1 to 3	1972 to 1983	185 km, 70 m	http://landsat.gsfc.nasa.gov
TM	Landsat 4 to 6	1982 to 2011	185 km, 30–120 m	
ETM+	Landsat 7	1999 to present	185 km, 15–60 m	
HRG	SPOT 4, SPOT 5	1998 to present, 2002 to present	55 km, 20 m, 55 km, 2.5–20 m	www.spot.com
MSI	RapidEye	2009 to present	77 km, 6.5 m	www.rapideye.de
LISS-III AWiFS	IRS-P6	2003 to present	140 km, 23.5 m, 740 km, 56 m	www.isro.org
CCD	CBERS-2 and 2B	2003 to present	113 km, 20 m	www.cbers.inpe.br
	Quickbird, WorldView-2	2001 to present, 2009 to present	16.5 km, 0.66–2.4 m, 16.4 km, 0.46–1.8 m	www.digitalglobe.com
	Ikonos, GeoEye-1	1999 to present, 2008 to present	11 km, 1– 4 m, 15.2 km, 0.41–1.6 m	www.geoeye.com

BOX 6.3
European Space Agency's Sentinel-2

An important future sensor for land cover applications is the European Space Agency's Sentinel-2, which will provide systematic global acquisitions of high-resolution multispectral imagery with a high revisit frequency and provide enhanced continuity of multispectral imagery provided by the SPOT series of satellites. The Sentinel-2 mission is envisaged to fly as a pair of satellites with the first planned launch in 2014. Each Sentinel-2 satellite carries a Multispectral Imager (MSI) with a swath of 290 km. It provides 13 spectral bands spanning from the visible and near infrared to the shortwave infrared, featuring 4 spectral bands at 10 m, 6 bands at 20 m and 3 bands at 60 m spatial resolution.

The United States of America's Landsat TM/ETM+ sensors have been the most widely used for land cover monitoring and there is now an extensive archive. However, the remaining operational satellite in the Landsat series is in a degraded status and subject to failure in the near future. NASA and the United States Geological Survey (USGS) are developing a follow-on initiative with the Landsat Data Continuity Mission (LDCM), which is expected to be launched in 2013. The French SPOT 4 and 5 are well-known commercial optical data sources with better spatial resolution compared with Landsat. SPOT 6, launched in September 2012, and Spot 7 (to be launched in 2014) will extend the SPOT programme at least until 2022. Additionally, the European Union supported high-resolution satellite Pleiades-1 was launched in late 2011 and Peliades-2 is due to be launched in 2013. Other commercial options referred to in Table 6.4 include RapidEye and the Disaster Monitoring Constellation (DMC). Each DMC satellite is owned by a partner nation and focuses mostly on daily image acquisition for their countries and provides imagery with a resolution similar to Landsat. RapidEye is a constellation of five satellites that can gather daily 5-m resolution multispectral images and is a cost-effective option. Several sub-metre spatial resolution optical satellites also exist, the best known being Quickbird (launched in 2001), WorldView-2 (launched in 2009), plus GeoEye-1 and Ikonos (launched in 2008 and 1999, respectively), with GeoEye-2 scheduled for launch in 2013. GeoEye-2 will be capable of discerning objects on the earth's surface as small as 0.25-m in size, which will provide the world's highest resolution and most accurate colour imagery. Section 6.5.2 provides information on obtaining optical image products.

6.3.2 Radar remote sensing systems and products

Radar imagery

Imaging radar do not penetrate water surfaces and interpretation is based on an understanding that radar "sees" or detects the surface differently to optical sensors, and characteristics such as surface roughness and (for soil or snowpacks) water content are important. An example application of imaging radar by Travaglia, *et al.* (2004) is provided in Section 6.8.1.

Several existing imaging radar satellites are described in Table 6.5. The different wavelengths of the sensors influence the way the radar interacts with objects or areas and thus the potential applications for fisheries and aquaculture. New imaging radar systems additionally provide information on the backscatter in different polarizations,[163] which can help a remote sensing specialist gain a better

[163] Polarization defines the orientation of the wave transmitted or received by a radar system, for example, "horizontal" (H) or "vertical" (V). For a more detailed definition, see Canada Centre for Remote Sensing: www.ccrs.nrcan.gc.ca/glossary/index_e.php?id=2818.

understanding of the properties of an object or area. Another advantage of the new imaging radar systems is the higher spatial resolution that can be achieved and multiple options for resolution and image swath size. However, the data may be considered expensive for many developing countries for fisheries and aquaculture applications. Important future developments include ESA's plan to launch two Sentinel-1 satellites with the first in 2013 and the second a few years later. Sentinel-1 will have a full and open Sentinel data policy (European Space Agency: www.esa.int/esaLP/SEMXK570A2G_LPgmes_0.html) and the Canadian Space Agency (CSA) is also planning a lower cost and more accessible RADARSAT Constellation (Canadian Space Agency: www.asc-csa.gc.ca/eng/satellites/radarsat). There are also plans for TerraSAR-X and ALOS-2 continuity. Section 6.5.2 provides some information on obtaining imaging radar products.

TABLE 6.5
Summary of radar remote sensing systems

Satellite sensor	Operational period	Swath width, spatial resolution	Band	Polarization	More information
ERS-1, ERS-2	1991 to 2000, 1995 to 2011	100 km, 30 m	C	VV	http://earth.esa.int/ers
Envisat ASAR	2003 to present	100–400 km, 30–150 m	C	Multi-polarization	
RADARSAT-1	1995–present	50–500 km, 9 m–100 m	C	HH	www.asc-csa.gc.ca
RADARSAT-2	2006 to present	8–500 km, 3–100 m	C	Multi-polarization	http://gs.mdacorporation.com/
TerraSAR-X	2007	10–100 km, 1.8–15 m	X	Multi-polarization	www.terrasar.de
ALOS PALSAR*	2006 to 2011	40–350 km, 10–100 m	L	Multi-polarization	www.eorc.jaxa.jp/ALOS/en

*Although this satellite ceased operations in mid-2011, its archived data is still valuable.

Ocean salinity

Passive radar detects the low levels of emitted microwave radiation from the earth's surface. The data have very coarse spatial resolution, meaning that they are not generally used for fisheries and aquaculture applications.

Launched in 2011, the joint Argentina and the United States of America Aquarius satellite provides monthly maps of global changes in ocean surface salinity with a resolution of 150 km, showing how salinity changes from month to month, season to season, and year to year at a global scale.
(www.nasa.gov/mission_pages/aquarius/news/aquarius20110922.html).

In 2010, the ESA Soil Moisture and Ocean Salinity (SMOS) satellite was launched and became operational. This satellite carries the MIRAS instrument (European Space Agency: www.esa.int/esaLP/ESAL3B2VMOC_LPsmos_0.html) to measure microwave radiation emitted within the L-band (1.4 GHz) using an interferometric radiometer. Of interest for global fisheries and aquaculture applications are the ocean salinity measurements that are provided by SMOS from late 2010; the goal is to observe open ocean salinity down to 0.1 practical salinity units (PSU) averaged over 10–30 days and with a coarse pixel size of approximately 200 × 200 km (for more information, see European Space Agency: www.esa.int/esaLP/ESAS7C2VMOC_LPsmos_0.html).

Sea surface conditions using radar altimetry

There has been an almost continuous series of radar altimetry missions starting with GEOSAT (1985) and measurements are currently continuing from JASON-1 (2001), Ocean Surface Topography Mission (OSTM) on JASON-2 (2008), and from Envisat RA-2 (2002). Altimeter systems are capable of measuring sea surface height (SSH), from which ocean circulation patterns and sea level are determined on a global scale. The ocean surface topography seen on Google Earth is derived using radar altimetry. Altimeter data are also used to compute significant wave heights (SWH) and wind velocity both of which are important for marine aquaculture. Section 6.5.2 provides some information on obtaining altimetry products.

Sea surface conditions from high frequency radar

High-frequency (HF) radar sea surface data requires investment in radar stations along the coastline of interest. HF radar now cover increasingly large areas of the United States of America, e.g. through the NOAA HF Radar National Server and Architecture Project (NOAA: http://hfradar.ndbc.noaa.gov), which provides a demonstration of the HF Radar display capability using Google Maps. HF Radar operates at long wavelengths (6–30 m) and requires two or more radars to be looking at the same area of water using two or more different viewing angles (CODAR: www.codar.com/intro_hf_radar.shtml). The complex radar processing allows precise information on the surface currents and wave heights, which can be provided in high spatial resolution (e.g. 1 km) and in real time (e.g. hourly).

6.4 REMOTE SENSING APPLICATIONS IN FISHERIES AND AQUACULTURE

The remote sensing systems described in Sections 6.2 and 6.3 have not been designed specifically to support fisheries and aquaculture management, and users take advantage of system capabilities mainly developed for broad applications in land surface mapping, weather forecasting and oceanography. The main applications of remote sensing for fisheries and aquaculture are in support of aquaculture development, aquaculture practice and management (including impact assessment), and for various aspects of marine fisheries monitoring and management. A small number of studies have looked at remote sensing applications to inland fisheries.

6.4.1 Aquaculture development

It is of interest to know where most of the work relating remote sensing to aquaculture is being undertaken. A recent analysis of the FAO Aquatic Sciences and Fisheries Abstracts (ASFA) database using the search criteria of “aquaculture + remote sensing” found 516 publications for the period 1996–2010. Table 6.6 shows the top 30 records by country (or marine area) in which the study took place, with these accounting for 333 of the publications. Another 167 of the records are not assigned to specific countries or regional seas because they focused on methodologies, etc. Although the United States of America dominates the publications, it is interesting that many of the rapidly developing countries are playing a major role in aquaculture applications of remote sensing, e.g. the People’s Republic of China, the Republic of India, the Socialist Republic of Viet Nam, the Democratic Socialist Republic of Sri Lanka, the United Mexican States, the Kingdom of Thailand and the Republic of Indonesia. In contrast, it is perhaps unexpected that so little work should be European based, i.e. with only four mentions in the top 30 and, indeed, with only one European country being mentioned. One-third of the areas listed are Asian countries and another third are named marine areas where the origin of the work is not defined.

TABLE 6.6
Number of publications recorded in the FAO ASFA database for 1996–2010 that link "aquaculture" to "remote sensing"

No.	Country/region	No. of applications
1	United States of America	89
2	China	43
3	India	29
4	Gulf of Mexico + Caribbean Sea	23
5	Canada	16
6	Viet Nam	12
7	North Atlantic	9
8	Sri Lanka	8
9	Australia	8
10	Japan	8
11	France	8
12	Mexico	7
13	Thailand	7
14	Indonesia	6
15	North Pacific	6
16	Indian Ocean	5
17	Antarctic	5
18	Arctic	5
19	South Atlantic	4
20	Brazil	4
21	Africa	4
22	North Sea	3
23	Baltic Sea	3
24	Mediterranean Sea	3
25	The Philippines	3
26	New Zealand	3
27	Colombia	3
28	South Africa	3
29	Bangladesh	3
30	Peru	3

Source: FAO (2012b).

The main issues addressed by remote sensing in aquaculture development are: (i) strategic planning for development; and (ii) suitability of site and zoning; each issue presents different data requirements. As summarized in Table 6.7, strategic planning for development deals with data at a relatively low resolution using a few key data sets to generate indicative results of aquaculture potential. Suitability of site and zoning require progressively more detailed data at higher resolutions, and analyses should provide relatively higher accuracy of results.

TABLE 6.7
Summary of the extent and resolution of GIS and remote sensing data and information needs for different tasks for aquaculture development

	Varying scales of aquaculture development tasks	
Characteristics relative to remote sensing requirements	Strategic planning for development	Suitability of site and zoning
Extent of analysis	Comprehensive at a large area of interest	Sub-areas within the large area of interest
Spatial resolution	Low	Moderate
Accuracy and precision	Indicative; general	Moderate
Sponsoring entities for the remote sensing tasks	Researchers, central government	Central and local governments
Scope of varied aquaculture input parameters required	Few; very basic, but broad in scope	Many; diverse and broad in scope

Offshore mariculture may offer significant potential for increasing world food production in an environmentally sustainable way. Kapetsky and Aguilar-Manjarrez (2010) illustrate that data from satellite remote sensing are indispensable to conducting estimates of the area suitable for offshore mariculture. Data wholly or partly from satellite remote sensing (i.e. sea surface temperature, chlorophyll-*a*, depth, and current speed) can be used to conduct the estimates of offshore mariculture potential. Furthermore, the build up of long time series of data and advances in data processing mean that series of daily, weekly, monthly, annual and seasonal "climatology" data are now readily available at increasingly higher resolutions that in turn will, in the near future, improve estimates of mariculture potential at all levels. In addition, emerging remote sensing products such as more reliable identification and tracking of harmful algal blooms will provide improved spatial and temporal risk assessment for operational management of mariculture.

Planning for aquaculture development requires understanding of the environment and assessing the suitability of a given region or site for a project to be sustainable. Several water quality and physical properties of the waterbodies of interest to aquaculture can be assessed by remote sensing, with some limitations related to the complexity of coastal environments. Remote sensing can meet part of the information needs; other important suitability data such as dissolved oxygen[164] cannot be determined from remote sensing and data such as salinity, ocean colour and currents may not be provided at sufficient temporal and spatial resolution from satellite remote sensing in coastal environments. To mitigate the issue of spatial resolution, airborne surveys have been conducted. In Indonesia, a CASI airborne survey was carried out by Populus *et al.* (1995) to map water type and, together with land use mapping, to make a preliminary assessment of the suitability of an area for shrimp aquaculture development. Rajitha, Mukherjee and Chandran (2007) refer to the capabilities of satellite remote sensing technology and GIS for the sustainable management of shrimp culture, especially to support prediction of water quality parameters. In Canada, the Ministry of Agriculture and Lands (Carswell, Cheesman and Anderson, 2006) surveyed an area of Vancouver Island's tidal zone with low altitude aerial photography for environmental assessment of shellfish aquaculture.

[164] In extreme cases levels of dissolved oxygen in marine waters may be inferred from remote sensing, e.g. if levels of chlorophyll-*a* are very high then this could be indicative of an algal bloom that can result in low dissolved oxygen levels.

In tropical areas, shrimp farming suitability and planning need to address sustainability issues concerning mangroves and coral reefs, which are important habitats for coastal fisheries. Mapping their extent using remote sensing is described in Green *et al.* (2000) and Mellina *et al.* (2009). Remote sensing derived data on coral reefs are available from the Millennium Coral Reef Mapping Project (USF Millennium Global Coral Reef Mapping Project: http://oceancolor.gsfc.nasa.gov/cgi/landsat.pl).

Satellite remote sensing also shows good potential for mapping the seafloor in shallow areas, but penetration of visible and infrared wavelengths through the water column is often limited and most high resolution sensors do not contain a blue visible band that provides for the best penetration.[165] High spatial resolution satellite imagery has demonstrated good potential for mapping coral reefs. SPOT 5 optical satellite imagery has been used in the Mediterranean by Pasqualini *et al.* (2005) to provide a method for mapping Posidonia oceanica, which is the dominant seagrass (more information is provided in Section 6.8.3).

6.4.2 Aquaculture practice and management

The main applications of remote sensing for aquaculture practice and management are: (i) inventory and monitoring of aquaculture and the environment; and (ii) environmental impacts of aquaculture.

Monitoring of aquaculture requires similar information on water quality and physical properties of waterbodies as those required for aquaculture planning described in Section 6.4.1 above. However, it is the temporal aspect of monitoring that is very important and applications must meet users' requirements related to the frequency of observation and the speed with which data and information are delivered to the users. Monitoring applications include regulators wanting to monitor development in the coastal zone, which can make use of both high and low resolution optical and imaging radar data. With reference to Table 6.7, monitoring of aquaculture operations has similar data needs as the siting of aquaculture structures. The extent of analysis would be focused on a single site or group of sites preferably with high spatial resolution; acceptable precision of parameters of interest (e.g. chlorophyll-*a*) can be more moderate because the data are required frequently and in real time.

The government as well as the private sector may be interested in monitoring. Remote sensing provides government agencies with capabilities to regularly monitor the extent of aquaculture development, and to check if it is proceeding according to marine spatial plans and/or regulations, or if it is adversely affecting the environment. De Graaf *et al.* (2004) used two types of satellite image – (IRS 1D) black and white images and multispectral (SPOT) colour images – to detect and map fish ponds in the People's Republic of Bangladesh. Imaging radar has supported land cover and aquaculture mapping and change detection, for example, Travaglia *et al.* (2004) demonstrated the potential of satellite imaging radar for mapping coastal fisheries and aquaculture structures in the Lingayen Gulf, the Philippines (see Section 6.8.1). Boivin *et al.* (2004) also described the potential for high resolution radar to monitor shrimp ponds and to detect if they are active, i.e. based on the aeration devices increasing water surface roughness. The United Nations Environment Programme (UNEP) Atlas of Our Changing Environment (UNEP: http://na.unep.net/atlas/webatlas.php?id=50) provides an example of using optical satellite imagery for monitoring the increase in large shrimp pond developments between 1987 and 1999 in the Gulf of Fonseca bordered by the Republic of El Salvador, the Republic of Honduras and the Republic of Nicaragua. Béland *et al.* (2006) demonstrated the use of a change detection methodology between 1986 and 1992, and 1992 and 2001 to assess mangrove forest alterations caused by aquaculture development in the district of Giao Thuy, the

---

[165] In 2010, Digital Globe launched WorldView-2, which has eight spectral bands including the blue band.

Socialist Republic of Viet Nam, which helped to assess the effectiveness of government measures taken to mitigate deforestation.

The near real-time delivery of remote sensing data and its integration with in situ data and models for monitoring the environment can provide timely information and even forecasts that are useful for aquaculture management. Recent progress in ocean colour imagery processing and the availability of catalogues of images processed for primary production and suspended matter open up new monitoring perspectives. Brown *et al.* (2005) describe the use of satellite imagery to identify the environmental conditions favourable for the occurrence of Emiliania huxleyi blooms in Chesapeake Bay, United States of America, which threaten local aquaculture. The blooms can also be distinguished from most other conditions in visible satellite imagery (e.g. SeaWiFS) by their milky white to turquoise appearance. In the Republic of Chile, a number of initiatives have been undertaken with the government and private aquaculture companies to develop near real-time ocean colour and SST remote sensing and hydrodynamic models as part of harmful algal bloom monitoring; e.g. Mariscope Chilean (Rodríguez-Benito, Alvial and Haag, 2003) and the ESA Chile Aquaculture Project (European Space Agency: www.esa.int/esaCP/SEMUS5AATME_index_0.html), which was implemented by Hatfield Consultants and ACRI-ST (see Section 6.5.2). Some of the challenges posed for remote sensing by complex coastal waters and environments are now less problematic further offshore; therefore, applications of remote sensing should allow for an increase in development and management of mariculture further off the coast and offshore.

The use of remote sensing coupled with GIS could be of immense value to developing or enhancing environmental impact assessment (EIA) related studies for assessing the potential impacts of aquaculture on coastal environments. In the Kingdom of Thailand, Patil, Annachhatre and Tripathi (2002) showed how a so-called geospatial EIA of potential shrimp farming sites offered advantages over a conventional EIA, where the geospatial EIA procedure involved sampling and analysis and the fitting of mathematical models for spectral reflectance data obtained from Landsat satellite imagery. More complex modelling applications are also possible, where a combination of different remote sensing data, in situ and biological data, are used to understand carrying or production capacity. For example, scientists from the French Research Institute for the Exploitation of the Sea (IFREMER) have conducted studies of the mussel and oyster production potential in the Bay of Mont St. Michel, the French Republic, in order to predict the production carrying capacity for existing sites as well as potential new sites (Thomas *et al.*, 2006). Kapetsky and Aguilar-Manjarrez (2007) summarize studies that have investigated carrying capacity for a range of aquaculture species.

6.4.3 Fisheries monitoring and management

As was shown for aquaculture in Section 6.4.1, it is useful to see where applications of remote sensing are being applied to fisheries monitoring or management. Table 6.8 shows the top 17 countries, as derived from the FAO ASFA database for the period 1996–2010 and using the search commands “marine fisheries + remote sensing”.[166] This search revealed 266 entries in total, of which 107 applied to no specific country or marine area. The United States of America is easily the foremost country for this work, but here the rest of the countries or areas show a fairly equal mix between developed and developing nations.

[166] Applications of remote sensing to inland fisheries by country or marine area have not been shown because total records for the 1996–2010 period was only 14, with eight of these not applying to any area or named inland water area.

Remote sensing has been relatively little used for inland fisheries, i.e. compared with its use in aquaculture and marine fisheries. However, some notable work has been accomplished. Malthus and George (1997) used Daedalus Airborne Thematic Mapper remotely sensed imagery to monitor the distribution of submerged aquatic macrophyte species in the Cefni Reservoir on the Isle of Anglesey, the United Kingdom of Great Britain and Northern Ireland. Remote sensing has been used to assess river channel geomorphic units (Wright, Marcus and Aspinall, 2000) and stream temperature (Torgersen *et al.*, 2001) to evaluate the suitability of fish habitat in streams and rivers. Although remote sensing technologies are becoming more commonplace in inland fisheries management, they are still relatively expensive to operate and require time intensive ground truthing to conduct the image classification and verify the classification results.

TABLE 6.8
Number of publications recorded in the FAO ASFA database for 1996–2010 that link "marine fisheries" to "remote sensing"

No.	Country/region	No. of applications
1	United States of America	59
2	North Pacific	12
3	India	11
4	Caribbean Sea + Gulf of Mexico	8
5	South Atlantic	7
6	China	7
7	Canada	7
8	Indian Ocean	6
9	North Atlantic	5
10	Australia	5
11	Africa	4
12	Mexico	4
13	New Zealand	2
14	Brazil	2
15	Norway	2
16	Portugal	2
17	Central America	2

Source: FAO (2012b).

Since the 1980s, satellite remote sensing has been used to support marine fisheries through locating potential fishing zones (PFZ) using temperature and productivity data to identify areas where fish tend to aggregate for feeding. In open ocean areas, chlorophyll-*a* and SST data show correlations in their values and gradients; cool waters detected using SST data typically indicate the upwelling of deep waters containing higher concentrations of nutrients. These nutrients support increased productivity in the euphotic zone that can be detected through increased chlorophyll-*a* in ocean colour images. A good review of fisheries information services and remote sensing is found in the IOCCG publication (Forget, Stuart and Platt, 2009). A commercial

PFZ system is provided by Catsat (www.catsat.com), which integrates radar altimetry and surface currents, SST, cloudless temperature (from passive radar), ocean colour, modelled subsurface temperature, marine meteorology, and global currents to provide information to fishing vessels. The Traceable and Operational Resource and Environment Data Acquisition System (TOREDAS) fisheries information system, providing estimates of optimal fishing areas (Forget, Stuart and Platt, 2009; Kiyofuji *et al.*, 2007) for Japanese waters, is described in the case study in Section 6.9.4. Vessel monitoring systems using satellite remote sensing are mature applications for national security, but many regions have also applied the systems to locate and monitor vessels for fisheries management. Radar is the mainstay of the systems, which usually include fully automated image processing and communication protocols with the authorities (Kourti *et al.*, 2005). Vessel detection rates depend on image type and vessel size, and vessel positions can be compared with reported positions. The systems, which can also be linked to fishery logbooks for the georeferencing of catches, provide surveillance for follow-up actions by authorities.

Platt and Sathyendranath (2008) review the potential ecosystem indicators that can be applied for detection of ecosystem change in response to environmental perturbations such as climate change or overfishing. They suggest that several indicators can be supported by remote sensing (ocean colour and SST), including the seasonal cycle and spatial variances of phytoplankton biomass and delineation of ecological provinces and phytoplankton size structure.

6.5 THE IMPLEMENTATION OF REMOTE SENSING

The implementation of remote sensing activities for fisheries and aquaculture is most likely part of a wider multidisciplinary programme, for example, involving fisheries scientists, GIS specialists and planning specialists. Implementation of remote sensing work and its integration with other components of a programme must be based on a well-defined need for data or information. Before selecting and acquiring remote sensing data and image processing, it is important to define clearly what information or outcome is expected to ensure that the final products deliver the information required.

6.5.1 Scoping study

A scoping study helps define the viability of the proposed activity and addresses important questions, such as those in Box 6.4. The scoping study requires an understanding of the basic characteristics of remote sensing as described in Section 6.2. The scoping study should determine if time and resources are available, if the activities are compatible with other proposed activities or existing operations, dependencies, establish cost-effectiveness, and address any administrative and legal requirements. From a technical perspective, the scoping study may result in some compromises because of the availability of imagery, software tools and resources. Data available from Internet portals and applications such as Google Earth may be helpful to support a scoping study.[167]

6.5.2 Selecting and acquiring remotely sensed data

After completing a scoping study, remote sensing data can be selected and acquired with confidence that such data should contribute to the overall project or programme objectives. Google Earth, Google Maps and/or Microsoft Bing Maps contain data that

[167] One of the potential limitations of Google Earth is that high-resolution optical imagery is not available over the ocean away from the coast, although this distance from the coasts is not consistent worldwide. This is likely due to a lack of available data, as Google largely relies on imagery provided by commercial aerial photography or satellite imagery that were originally commissioned or purchased by governments or by other commercial clients. Now that Google is investing more in imagery, including investing in the GeoEye-2 satellite, the situation may improve and Google Earth certainly is an excellent source for many coastal and terrestrial areas.

BOX 6.4
Important questions to address in a scoping study

- What are the overall goals and objectives of the programme? For example, identify areas of national economic exclusive zones (EEZs) suitable for marine aquaculture. If the needs are not documented, a needs assessment is required.
- What is the area of interest? For example, a national EEZ, a small inlet or a freshwater lake. The size of area of interest and the complexity of the coastline or landscape will influence the type of remote sensing data that are appropriate.
- What spatial scale and/or spatial resolution are desired? For example, mapping scale of 1:10 000 or spatial resolution of 1 metre.
- What is the frequency of data required, how quickly does it need to be delivered, and for what time period? For example, daily chlorophyll-a data delivered in near real-time for algal bloom monitoring for a high-risk six-month period.
- Can existing data address the information needs?
- Can information provided by remote sensing meet project needs? For example, ocean productivity (chlorophyll-a).
- Do remote sensing data need to be integrated with other data and models?
- What is the available budget to buy imagery and complete image processing for the duration of the programme?
- What expertise and tools are available to process and integrate the remote sensing data? For example, a radar remote sensing specialist and image processing software.

can be browsed, but a scientific study will probably need to access original data. There are many global and regional sources of satellite remote sensing data. It is important to investigate the freely available data first. National government departments or agencies may have unique archives for several sensors, including Landsat TM, and this material may be freely obtained. The following subsections provide information on sources of remote sensing data and information products. Of particular interest for marine aquaculture and marine fisheries are long-term ocean “climatologies” (multiyear mean, variance and anomalies) and near real-time data, which if integrated with models could be used to provide forecasts.

Data are also available according to different “data levels” (see Section 6.2.1), which describe the amount of processing that the data supplier has conducted before the product is made available to the user. The simplest approach for non-specialists is to start with the higher-level data because they are most likely to be products that can be directly integrated within a GIS and used for analysis. It is also important to review the metadata (information about the data) to ensure that the parameters provided by the product, format and level are understood. Metadata is often summarized in a data specification document or a text file.

Sea surface temperature

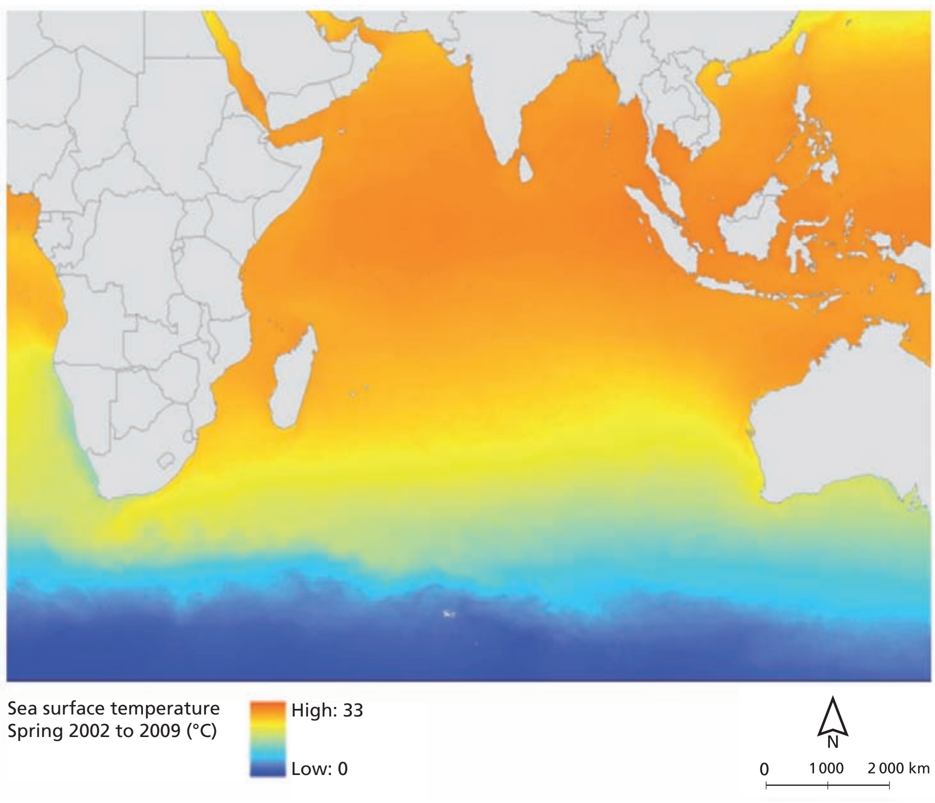
Table 6.9 provides an overview of popular sources of SST data. The Group for High Resolution Sea Surface Temperature (GHRSST: www.ghrsst.org) provides operational access to nearly all satellite SST data sets in a common format and within several hours of acquisition by the satellite instrument. GHRSST products (typically 10–50 km spatial resolution) are generated by combining complementary satellite and in situ observations within “optimal interpolation” systems. Several high spatial resolution (< 5 km resolution) regional SST analysis products are available; e.g. from ESA for the Mediterranean (based on the Medspiration project).

TABLE 6.9
Sources of SST data and information products

Source	Details	Access
NOAA	4 km AVHRR Pathfinder Project: 4 km global product provides long-term SST "climatologies", including mean, variance and anomalies.	www.nodc.noaa.gov/SatelliteData/pathfinder4km (Free)
GHRSST	Level 4 gridded SST products (typically 10–50 km spatial resolution)	www.ghrsst.org (Free)
Rutgers University	AVHRR: Real-time and archive SST daily composite for the eastern United States of America, including the Gulf of Mexico.	http://marine.rutgers.edu/mrs/sat_data (Free)
MyOcean	Provides access to a range of regional and global SST data, including GHRSST.	www.myocean.eu.org (Free)

Complementary to GHRSST, SST data products are also provided by national agencies that operate SST-related missions. The 4 km AVHRR Pathfinder Project, as the name suggests, has produced a 4 km global coverage product using the AVHRR sensor series for the entire 1985–2001 time series; a sample is shown in Figure 6.6. A good source of oceanographic information, especially for Europe, is the MyOcean Service. More information on accessing data through Google Earth and integration into ArcGIS is provided in Section 6.7.

FIGURE 6.6
Demonstration of the global 4 km AVHRR pathfinder project sea surface temperature product for the Indian Ocean



Source: ESRI (2010); NASA (2012).

Ocean colour

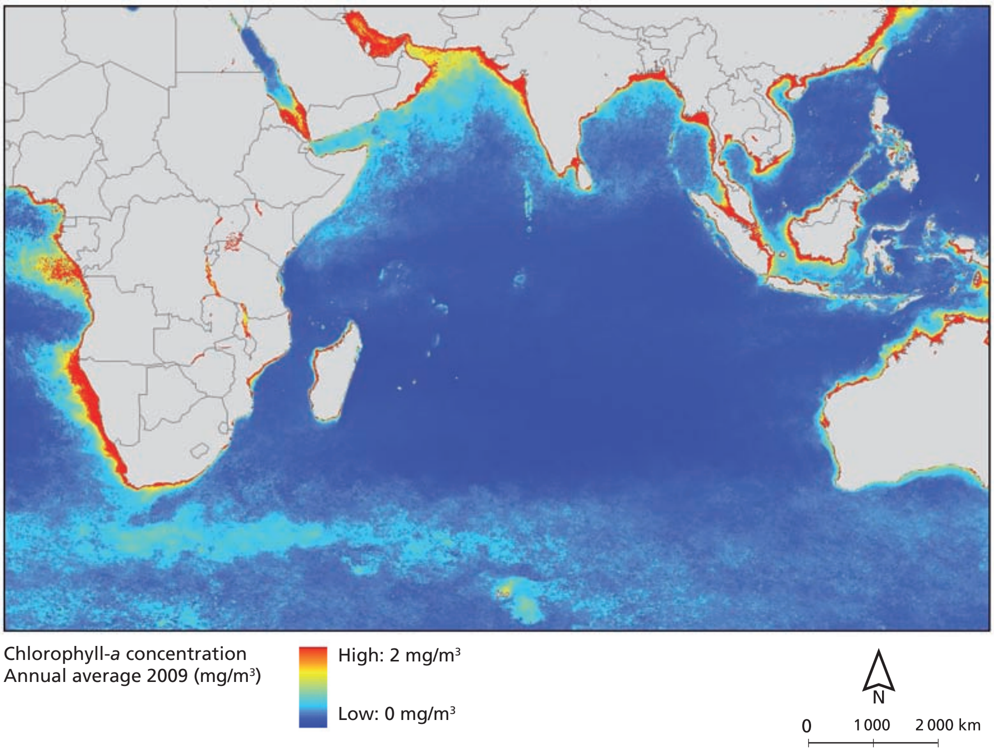
Table 6.10 provides an overview of popular sources of ocean colour data. The ESA DUE GlobColour project has merged observations made with different satellite systems to enable global daily coverage. GlobColour provides time series from 1997 to the present of consistently calibrated and validated global ocean colour information with a 4.6 km spatial resolution coverage (see Figure 6.7). The ESA DUE GlobColour project is continued in the context of MyOcean (EU FP7). A pilot Web-based harmful algal bloom warning system for the Chilean aquaculture sector is described as a case study in Section 6.9.2, which used MERIS and MODIS remote sensing data. In addition, the NASA Ocean Color[168] Web provides access to CZCS, SeaWiFS, MODIS level 1 to 3 data, including daily, weekly, monthly and seasonal climatologies. Other regional ocean colour services exist, including NOAA Coastwatch and the Canadian Department of Fisheries and Oceans.

TABLE 6.10
Sources of ocean colour data and information products

Source	Details	Access
GlobColour/ HERMES	Merging of MERIS, SeaWiFS and MODIS level-2 data: daily, weekly and monthly Level 3 products (15-day delay or daily near real-time). Extraction of ocean colour data for user-defined areas is possible and a free GlobColour subscription service allows users to systematically obtain near real-time products at 1 km spatial resolution for a specific area.	http://hermes.acri.fr/ (free, with commercial services offered)
NASA Ocean Color Web	CZCS, SeaWIFS, MODIS level 1 to 3 data: Daily, weekly, monthly and seasonal climatologies.	http://oceancolor.gsfc.nasa.gov (free)
ESA	MERIS level 1, 2, 3.	http://envisat.esa.int/level3/meris (free)
NOAA Coastwatch	Provides access to multiple satellite ocean remote sensing data and products for selected marine zones of the United States of America.	http://coastwatch.noaa.gov (free)
MyOcean	As part of MyOcean, the ACRI-ST Global Ocean Colour Processing Unit provides access to a range of regional and global ocean colour data, including GlobColour.	www.myocean.eu.org or http://hermes.acri.fr (free)

[168] Ocean colour refers to information about the optical properties of the ocean, including parameters such as concentration of chlorophyll-*a* and suspended sediment.

FIGURE 6.7
Example of GlobColour ocean colour data product for chlorophyll-*a* concentration



Source: ESRI (2010); ACRI-ST (2012).

Optical and radar data for inland and coastal zone mapping

Table 6.11 provides an overview of popular sources of optical and radar imagery products. National government departments or agencies, and other regional departments, may also have data archives that are worth investigating. For optical data, there are a huge range of government and commercial suppliers; and only a sample of the well-known suppliers is provided here. For commercial products, there will be a reseller or distributer in most countries, or at least a regional office (e.g. Spot Asia in Singapore). It is better to start exploring the lower resolution data such as Landsat TM/ETM+ and ASTER first before purchasing more expensive higher resolution imagery. A good option to begin exploring imaging radar data is ALOS PALSAR, because there is a systematic observation strategy to acquire imagery on a regular basis (JAXA EORC www.eorc.jaxa.jp/ALOS/en/obs/overview.htm) and the data are not expensive. Under the ALOS Kyoto and Carbon Initiative, there is a free 50 m and 500 m resolution PALSAR mosaic available, including a Google Earth KML file. For a research and development project, it is also possible to apply to propose a "Category 1" (CAT-1) project to ESA that can provide radar data (Envisat ASAR and ERS) at the cost of reproduction with some products free via a Web server (see EOPI: http://eopi.esa.int/esa/esa?cmd=aodetail&aoname=cat1).

TABLE 6.11
Sources of optical and imaging radar data products

Source	Details	Access
Optical		
SpotImage	SPOT, Ikonos, GeoEye: SpotImage, a regional network supply with a range of commercial imagery, including SPOT, Ikonos, GeoEye-1. Reseller list for new acquisitions	www.spotimage.com (commercial)
Landsat.org	Landsat: Entire current global collection of Landsat ETM+. Searchable online catalogue and downloadable data.	www.Landsat.org (mostly free)
Tropical Rain Forest Information Center	Landsat: Searchable online catalogue and downloadable data.	www.trfic.msu.edu/ (mostly free)
Global Land Cover Facility	Landsat, ASTER, others: Searchable online catalogue and downloadable data.	http://glcf.umiacs.umd.edu (mostly free)
GloViS	Landsat, ASTER: USGS Global Visualization Viewer (GloVis) online catalogue and ordering.	http://glovis.usgs.gov/ (Mostly free)
TerraLook	ASTER: Provides access to satellite images for users that lack prior experience with remote sensing or GIS.	http://asterweb.jpl.nasa.gov/TerraLook.asp (free)
GeoEye GeoFuse	GeoEye-1, Ikonos: A browseable archive integrated with Google Maps and Google Earth. Reseller list for new acquisitions.	http://geofuse.geoeye.com/ (commercial)
Digital Globe	Quickbird and WorldView: ImageFinder browseable archive. Reseller list for new acquisitions.	www.digitalglobe.com (commercial)
RapidEye	RapidEye: Geodata Kiosk online data store, submit new acquisitions.	http://kiosk.rapideye.de/datadoorsweb/Order.aspx (commercial)
Radar		
JAXA	ALOS PALSAR: 50 m and 500 m Mosaic, including data, image and Google Earth KML files.	www.eorc.jaxa.jp/ALOS/en/kc_mosaic/kc_mosaic.htm (free mosaic)
CROSS	ALOS PALSAR: Searchable online catalogue.	https://cross.restec.or.jp/ (commercial, cost effective)
eoPortal	ASAR and ERS and others: Searchable online catalogue, particularly useful for searching ESA archives.	http://catalogues.eoportal.org (free and cost-effective)
Infoterra	TerraSAR-X: Downloadable archive file for GIS software, plan new acquisitions.	www.infoterra.de (commercial)
MDA Geospatial Services	RADARSAT-1 and 2 and others: Contact for new acquisitions and archive.	http://gs.mdacorporation.com/ (commercial)

Radar altimetry

Table 6.12 provides an overview of the main sources of radar altimetry-based products. AVISO distributes satellite altimetry data from Topex/Poseidon, Jason-1, ERS-1 and ERS-2, and Envisat in near real-time on a daily basis. AVISO products include a 25 km spatial resolution "geostrophic current" product, significant wave height (SWH), and surface winds. ESA has recently established the GlobWave project, with support from the French space agency (CNES), to provide satellite-derived wave products to users around the globe. The project will provide free access to satellite wave data and products in a common format, both historical and in near real-time.

TABLE 6.12
Sources of radar altimetry products

	Details	Access
AVISO	Geostrophic currents, significant wave height, and surface winds	www.aviso.oceanobs.com/en/data/products/ (free, with commercial services offered)
GlobWave	Satellite wave data products (under development)	www.globwave.org/ (free)
MyOcean	Provides access to a range of regional and global ocean data, including AVISO products.	www.myocean.eu.org/ (access to free data)
eoPortal	ASAR and ERS and others: Searchable online catalogue, particularly useful for searching ESA archives.	http://catalogues.eoportal.org/ (access to free data)

6.5.3 Costs of data

The cost of remote sensing data varies considerably, i.e. considering that some data are provided freely by international or national space and oceanographic agencies and others are commercial products where a company is trying to run a profitable business based on data sales. Google Earth contains a very valuable range of high spatial resolution data that can be browsed freely.

In almost all cases, the end users must make some compromises on the data they would like to use and what is practically and economically possible. For example, it may be desirable to have up to date, 1 m spatial resolution optical data for the entire coastal zone for a country or province, but this may be prohibitive in terms of cost and the data volumes may be hard to manage. Costs of imagery are not the same in different regions. For example, countries with satellite receiving stations often have lower government pricing for imagery (e.g. RADARSAT in the People's Republic of China). Space agencies may reduce pricing for their imagery in developing countries, e.g. ESA in Africa or JAXA for parts of Southeast Asia.

As described at the start of this section, it is best to first investigate what your own national government departments or agencies have available. The range of potential applications and size of areas of interest is obviously an important factor. It is important to remember that there are costs associated with fieldwork, image processing and analysis, accuracy assessment and cartography that must also be considered. Development of Web-based or desktop information management systems for remote sensing applications will often greatly exceed the data costs, depending on labour costs in the region. A scoping study is an essential step to determine if a proposed activity or application is economically feasible and sustainable.

As an indicative guide, the typical cost of data for some common fisheries and aquaculture applications is provided in Table 6.13. The total cost for data in the table is the cost before image processing; however, data products can be purchased at these prices (with the exception of ALOS PALSAR) with certain image processing already completed (e.g. geometric correction described in Section 6.6.3). The number of images is also estimated, although this depends on the shape of the area of interest, and many products are now available at prices based on the area of data required rather than images or "scenes". It is very important to appreciate that prices change and the market for satellite data is becoming more competitive.

TABLE 6.13

Indicative costs of satellite image data for two typical fisheries and aquaculture applications

	Mapping aquaculture structures		Coastal vegetation mapping	
Area of interest size	1 000 km^2		5 000 km^2	
Sensor type	Imaging radar		Multispectral optical	
Data type/mode	ALOS PALSAR, fine beam	TerraSAR-X, StripMap	RapidEye	SPOT 5
Spatial resolution (m)	10	3	5	5
Estimated number of images	1	1	2	2
Example mapping scale	1:30:000	1:15 000	1:20 000	1:20 000
Cost (US$/$km^2$)	0.5–1	5–8	1.5–2.5	2.5–3
Total cost for data (US$)	500–1 000	5 000–8 000	7 500–12 500	12 500–15 000

6.6 PREPARING REMOTELY SENSED IMAGERY FOR GIS USE

Once remotely sensed imagery has been acquired, it is almost certain to require some processing. Most processing tasks can be undertaken via the use of specialist image processing software such as ERDAS or ENVI, though there are a number of proprietary GIS software that includes image processing and other editing functions, e.g. IDRISI, ArcGIS and Manifold. The following site provides access to free image processing software (FreeGIS.org: www.cof.orst.edu/cof/teach/for421/Software.html), though the site does not include OSSIM (www.ossim.org) and ILWIS (www.ilwis.org). See Section 6.7.4 for further details on remote sensing software.

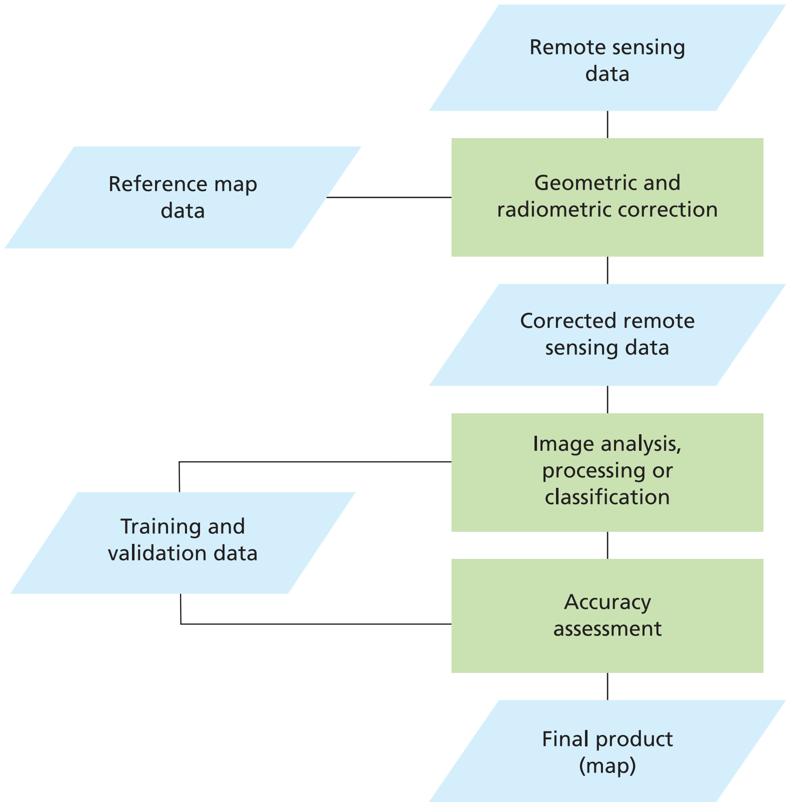
Image processing includes all activities that are performed with the imagery or data in order for it to be useable for the desired application, i.e. before possible integration into a GIS. Depending on the applications, there may be very little or no processing required, e.g. a chlorophyll-*a* product from NASA Ocean Color Web could be directly integrated into a GIS. Alternatively, significant image processing may be required using specialized software, e.g. using radar data for mapping aquaculture ponds. Figure 6.8 and the following subsections briefly describe some main steps in image processing. The Canada Centre for Remote Sensing (www.ccrs.nrcan.gc.ca/resource) provides good outreach materials in English and French related to image processing.

6.6.1 Reference map data

To locate ground features on imagery, or to compare a series of images, a geometric correction procedure is used to register each pixel to real world coordinates (Jensen, 1996). Many types of remote sensing data can be acquired with a defined coordinate system and datum, and the data can be directly integrated in a GIS with other map data. The metadata and the reported accuracy of geometric corrections should be reviewed to determine if they meet user requirements, and care is required if re-projecting data (see Section 3.3.4). It is also possible to order and receive data without any geometric corrections, and to perform corrections using specialized image processing software. Often this is considered to provide more accurate results, as the user should have access to "ground control points" or reference map data that can be used to precisely and accurately identify locations on the map. For terrestrial applications, a digital elevation model (see Section 5.8.3) is also required to ensure that the geometric distortions caused by terrain can be corrected.

To compare imagery from different places or dates, the impact of illumination and atmospheric effects should be removed from the imagery – this is "radiometric correction". Similar to geometric distortions, many available products have been

FIGURE 6.8
Typical activities in remote sensing image processing



processed to remove atmospheric and illumination distortions, e.g. ocean colour or SST data. Other optical or radar data may not have been corrected. Radiometric correction is often one of the more challenging stages in image processing for many users and requires more sophisticated software tools and knowledge. Therefore, it is important that remote sensing imagery acquired should be already in a trustworthy and useable form.

The output from geometric and radiometric correction is "corrected remote sensing data" that can be further assessed and analysed.

6.6.2 Training and validation data

Often called "ground truth" or "sea truth",[169] supporting data are an important input to most remote sensing projects. For example, ground truth can include land cover observations (vegetation types) and sea truth data can include in situ measurements (direct water temperature measurements). The ground or sea truth data often has two purposes: (i) to help develop the product; and (ii) to help assess the accuracy of the product.

When ground or sea truth data are used for product development they are often called "training data". When used for accuracy assessment, the data are referred to as "validation data." As described in Section 6.6.4 on accuracy assessment, it important that the same ground or sea truth data are independent and not used for training and accuracy assessment because then the accuracy statistics may be biased.

[169] Readers might see the processes involved in relating the imaged data to the real on-the-ground data as "ground truthing" or "sea truthing".

6.6.3 Image analysis, processing or classification

Thematic mapping or image classification and analysis, or "retrieval" of biophysical parameters such as chlorophyll-*a* or SSH, can be included under image analysis. Usually the biophysical modelling is conducted by skilled specialists and only the validated products are integrated into GIS (e.g. GlobColour or AVISO products). On the other hand, optical imagery and imaging radar are more often analysed by GIS specialists with remote sensing knowledge.

There are many methods and approaches for thematic classification of satellite data, which range from visual interpretation and classification to almost fully automated classification (see Table 6.14). Automation has the potential to save costs by minimizing the time required for manual editing; however, inappropriate automation could result in increased costs owing to time-consuming manual revisions of automated products. The best option can be semi-automated approaches, where the manual delineation and interpretation process is supported by inputs from automated classification approaches.

The output of image analysis, processing or classification is a thematic product that can be evaluated in an accuracy assessment.

TABLE 6.14
Advantages and disadvantages of thematic classification approaches

Visual interpretation	Semi and fully automated
Advantages • Can on-screen digitize using GIS software, no specialist software required • Accurate and pleasing thematic map, if work is completed by a skilled image analyst and there are good interpretation guidelines • Better feature or object extraction, especially linear features • Delineation and attribution can be achieved in a single step	**Advantages** • Faster • Cheaper (depending on labour costs) • More repeatable, e.g. for future updates • New software can identify objects or features • Can be more efficient for large mapping projects, or operational services
Disadvantages • Classification may not be easily repeatable by different people • Time consuming • Costly (depending on labour costs) • Needs skilled interpreters	**Disadvantages** • Requires specialist knowledge and understanding of different options • May require specialist and expensive software, although there are now several open source options • Processing and results will require manual work to create a thematic map

6.6.4 Accuracy assessment

An accuracy assessment or validation report provides important information to the users of the products that have been derived from remote sensing, but it is too rarely performed. The accuracy assessment uses the part of the validation data not used for the product development (i.e. independent data) and these values are cross-checked with the classified remote sensing product. Quality georeferencing is important so that the location of the validation samples is accurate. Authors must also describe how their assessment was performed and refer to well-established standards; a useful review was provided by Congalton (1991).

Product accuracy is very important when change detection analysis is performed (post-classification comparisons) because errors in each product can be compounded. Users should exercise caution in analysing the differences recorded by their maps as map inaccuracies almost invariably compromise their change estimation (Fuller, Smith and Devereux, 2003).

Following an accuracy assessment, the output of image analysis, processing or classification is a thematic product where users of the product can understand the limitations and suitability of the product for their application.

6.7 CHANGE DETECTION

A time series of images, created by repeated image acquisition over the same location, can be used to assess change. There are many approaches and methods of change detection analysis depending on the application. Usually a "baseline" image or reference image is defined and other images are directly compared. Some popular approaches include:

- Manual change detection is the simplest approach and is commonly used for land cover change mapping. An experienced image analyst visually compares two or more images and identifies changes in land cover. The areas and types of change are digitized using GIS software. Because this approach relies on visual interpretation, it is important to ensure that the rules for interpretation are defined so that the analysis is standard and repeatable.
- Comparing classified images. The images from each date are classified (following the same method) and the change between them is analysed. The analysis is normally performed using a GIS, which also allows for the integration of other data such as management units and administrative boundaries.
- Direct change detection. A baseline image and a new image are compared directly. Differences in the image values are used to identify areas of environmental change. Local knowledge and validation data are required to interpret what the change is, for example, mangrove loss.

Regardless of the method used to detect change, images should be geometrically corrected and coregistered so that they can be compared in a standard and direct way. More advanced image processing may also be required in order to remove the bias of factors such as different solar illumination and atmospheric conditions on the dates that the satellite images were collected.

6.8 TECHNICAL SUPPORT AND TRAINING FOR REMOTE SENSING

The following subsections introduce some resources (Web sites, organizations, references) giving further information and technical support for remote sensing applications for fisheries and aquaculture.

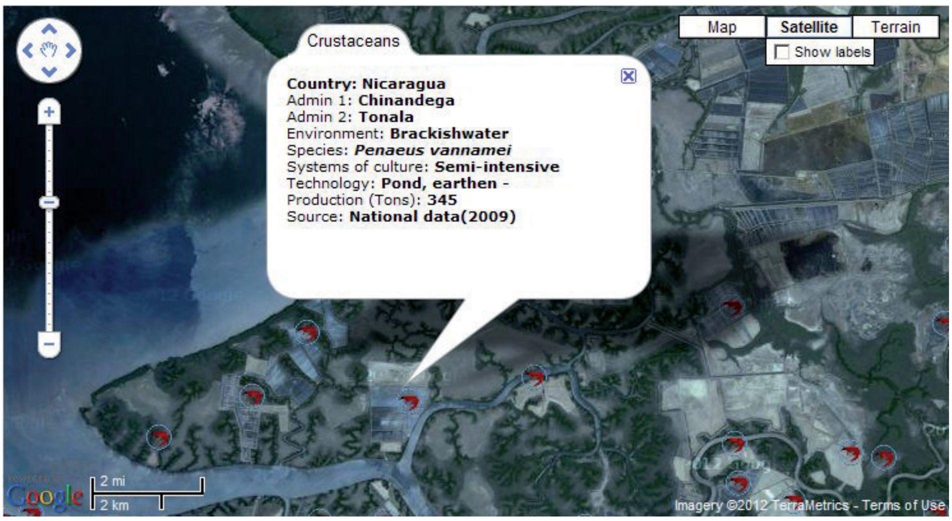
6.8.1 Web resources and organizations

As well as providing mixed resources to aid in the use of remote sensing, some of the sites listed below provide a much wider range of materials such as data, tools, publications, etc that are useful to fisheries, aquaculture and marine applications of GIS.

- **GISFish (www.fao.org/fishery/gisfish/index.jsp)** – Managed by FAO, GISFish is a "one stop" site from which to obtain the global experience on GIS, remote sensing and mapping as applied to fisheries and aquaculture. GISFish sets out the issues in fisheries and aquaculture and demonstrates the benefits of using GIS, remote sensing and mapping to resolve them. The global experience provided by GISFish is captured in issues, publications, activities, training, data and tools, contacts, discussions, news and events. Using the "Data and Tools" menu of GISFish, access is gained to a wide range of inland fisheries and aquaculture associated data including links to remote sensing data and tools.
- **Census of Marine Life (http://comlmaps.org/how-to/layers-and-resources)** – Produced an excellent Layers and Resources section for their Web site where there are simple instructions for data download and data conversion for many of the data sets described in this chapter.

- **International Ocean Colour Coordinating Group (www.ioccg.org)** – is a useful resource to understand ocean colour data. The IOCCG has published several useful reports, including remote sensing in fisheries and aquaculture (Forget, Stuart and Platt, 2009), and conducts and sponsors advanced training courses on applications of ocean-colour data in various developing countries.
- **Marine Geospatial Ecology Tools (MGET; http://code.env.duke.edu/projects/mget)** – for ArcGIS provides a geoprocessing toolbox of more than 180 tools for coastal and marine researchers and GIS analysts who work with spatial ecological and oceanographic data;
- **National Aquaculture Sectors Overview (NASO) Maps Collection (www.fao.org/fishery/naso/search/en)** – The NASO map collection consists of Google maps showing the location of aquaculture sites and their characteristics at an administrative level (state, province, district, etc.) and in some cases even at an individual farm level. The data are being collected by country experts, and the detail available depends on the degree of aquaculture development in each country, the resources available for data collection and the level of clearance provided to publish data (see Figure 6.9).
- **Remote sensing for decision-makers – aquaculture study and lagoon management: pilot study in Morocco (www.fao.org/SD/eidirect/EIre0068.htm)** – An aquaculture case study from a series on the use of remote sensing and GIS in management of renewable natural resources in agriculture, forestry and fisheries. The series is intended for managers and division directors of national and international organizations and administrations, as well as for project managers, planners and policy-makers at development institutions.
- **SAFARI project (www.geosafari.org) – the IOCCG co-sponsors the project, which was developed under the umbrella of the Group on Earth Observations (GEO) (www.earthobservations.org)** – The SAFARI project aims to accelerate the pace of assimilation of remote sensing data into fisheries research and ecosystem-based fisheries management on a world scale.

FIGURE 6.9
Illustration of part of the NASO map collection for Nicaragua



Source: FAO (2012c).

6.8.2 Book resources

The following provides a selection of popular remote sensing reference books:

- Campbell (2008) – Introduction to Remote Sensing (Third Edition) – a popular text that introduces students to widely used forms of remote sensing imagery and their applications in plant sciences, hydrology, earth sciences and land use analysis.
- Cracknell (2007) – Introduction to Remote Sensing (Second Edition) – a comprehensive introduction covering the physical principles of common remote sensing systems, processing, interpretation, and applications of data. This edition features updated and expanded material, including greater coverage of applications from across earth, environmental, atmospheric and oceanographic sciences.
- Lillesand, Kiefer and Chipman (2007) – Remote Sensing and Image Interpretation (Sixth Edition) – a comprehensive introduction to the latest developments in the field of remote sensing and image interpretation. Examines the basics of analog image analysis while placing greater emphasis on digitally based systems and analysis techniques. The presentation is discipline neutral, so students in any field of study can gain a clear understanding of these systems and their virtually unlimited applications.
- Martin (2004) – An Introduction to Ocean Remote Sensing – Examining the use of satellite data in the retrieval of oceanic physical and biological properties, this book presents examples of the kinds of data that can be acquired and their oceanographic application. The textbook, designed for graduate and senior undergraduate courses in satellite oceanography, will prepare students and interested scientists to use satellite data in oceanographic research.
- Mesev (2007) – Integration of GIS and Remote Sensing – explores the potential that lies along the interface between GIS and remote sensing for activating interoperable databases and instigating information interchange. It concentrates on the rigorous and meticulous aspects of analytical data matching and thematic compatibility – the true roots of all branches of GIS and/or remote sensing applications.
- Rees (2001) – Physical Principles of Remote Sensing – aimed at students and researchers in remote sensing, geography, cartography, surveying, meteorology, earth sciences and environmental sciences generally, as well as physicists, mathematicians and engineers. This text covers the subject matter mainly from the physics viewpoint.
- Tan (2011) – Remote Sensing of the Changing Oceans – is a comprehensive account of the basic concepts, theories, methods and applications used in ocean satellite remote sensing, and it also includes new developments in satellite remote sensing technology and international cooperation in this emerging field.
- The whole of the ICES Journal of Marine Science (Vol. 68. No. 4, 2011) is given over to symposium reports on remote sensing in fisheries.

6.8.3 Technical training materials

- **Canada Centre for Remote Sensing (CCRS) (www.ccrs.nrcan.gc.ca/resource)** – Remote sensing outreach materials in English and French. Includes an excellent glossary of remote sensing terms.
- **NASA Remote Sensing Tutorial (http://rst.gsfc.nasa.gov)** – An online training manual for learning about remote sensing. The tutorial was updated in March 2010.
- **ESA EduSpace (www.esa.int/SPECIALS/Eduspace_EN/index.html)** – The Eduspace Web site aims to provide secondary school students and teachers with learning and teaching tools. It is meant to be an entry point for space image data, and, in particular, to a widespread visibility of earth observation applications for education and training. The Web site provides a good and accessible introduction to remote sensing that should appeal to non-specialists.

- **NOAA Coral Reef Watch Remote Sensing Tutorial (http://coralreefwatch.noaa.gov/satellite/education/reef_remote_sensing.html)** – Provides a curriculum aimed at grade four to six students in remote sensing and coral reefs, but the content is applicable for older age groups and any non-remote sensing specialist who wants a good introduction to the application.
- **Columbia University Remote Sensing Image Analysis Laboratory, Remote Sensing Glossary (www.ldeo.columbia.edu/res/fac/rsvlab/glossary.html#S)**.
- **UNESCO-BILKO (www.noc.soton.ac.uk/bilko)** – Bilko is a complete system for learning and teaching remote sensing image analysis skills. Current lessons teach the application of remote sensing to oceanography and coastal management, but Bilko routines may be applied to the analysis of any remote sensing image in an appropriate format and include a wide range of standard image processing functions.

6.8.4 Software and tools

It is important to explore different free and/or open source GIS and remote sensing software, to discover if software can support the analysis required. An index of some open source projects is found at http://opensourcegis.org; some good free remote sensing options are listed below:

- **BEAM (www.brockmann-consult.de/cms/web/beam)** – Toolbox and development platform for viewing, analysing and processing of medium resolution remote sensing data from MODIS, MERIS, AVHRR, AVNIR, PRISM and CHRIS/Proba. Various data and algorithms are supported by dedicated extension plug-ins.
- **Fusion (http://forsys.cfr.washington.edu/fusion/fusionlatest.html)** – A powerful LIDAR viewing and analysis software developed by the Remote Sensing Applications Center of the United States Department of Agriculture (USDA) Forest Service.
- **Google Earth (http://earth.google.com)** – Version 6.0 of Google Earth contains a range of oceanographic and other data in the Ocean Layer. For example, the United States Navy's Daily, Dynamic SST. Many other organizations provide access to Google Earth KML files to explore land, coastal and ocean data.[170]
- **ILWIS (www.ilwis.org)** – GIS software with a comprehensive set of image processing tools and capabilities for image georeferencing, transformation and mosaicing
- **Nest ESA SAR Toolbox (NEST; http://earth.esa.int/nest)** – NEST is an ESA toolbox with an integrated viewer for reading, post-processing and analysing ESA and third party SAR data. NEST allows users to further develop the software package by means of a Java Application Programming Interface (API). NEST is developed by Array Systems Computing Inc. under contract to ESA.
- **Opticks (http://opticks.org)** – An expandable remote sensing and imagery analysis software platform
- **Radar Tools (RAT; http://radartools.berlios.de)** – Tool for processing radar data. Advanced algorithms in SAR polarimetry (PolSAR), interferometry (InSAR) and polarimetric interferometry (PolinSAR) are included.

[170] Google generally focuses on providing imagery over land and coastal areas, although more attention has been recently directed at exploring the oceans of the world with the development of Google Ocean (http://earth.google.com/ocean) (S. Bradt, personal communication, 2012). It is advisable to keep the Google Earth installation up to date because since version 5 there is an easy way to check the date of the satellite imagery – simply by holding the cursor over the centre of the image and the acquisition date appears at the bottom of the image. The toolbar of the latest version also contains an excellent "historical image time slider", which enables the user to easily review multitemporal imagery if it exists. Because Google Earth is regularly updated and enhanced, it is recommended to check the Web site and keep the software up to date.

A few examples of some of the main proprietary remote sensing software are listed below:

- **ERDAS IMAGINE (www.erdas.com/products)** – Claims to be the brand leader in image analysis software.
- **ENVI (www.ittvis.com/language/en-us/productsservices/envi.aspx)** – This is also a leading proprietary supplier of image analysis software.
- **ArcGIS (www.esri.com)** – ArcGIS is the leading commercial GIS software package, offering an integrated collection of GIS software products. There are numerous extensions to the software, some of which are free such as MGET (described above).
- **IDRISI (www.clarklabs.org)** – As a commercial GIS and remote sensing software, it is relatively cheap, user friendly and very powerful.
- **Manifold (www.manifold.net)** – Manifold is a cost-effective GIS software package that can be used to integrate a variety of oceanographic data in available formats.

6.8.5 Data formats

A key challenge for many non-remote sensing or GIS specialists is the range of data formats and projections in which remote sensing and oceanographic data are provided. Even the most common data formats can be confusing to those who are not programmers or remote sensing and GIS specialists. Some effort and time is required to learn how to use available data and tools, but there is substantial user guidance available. Table 6.15 provides a summary of the common data formats for remote sensing and oceanographic data and reference to some of the tools for viewing and converting the data. It is also important to review the "metadata" (information about the data product) to ensure that the parameters provided by the product, format and level are understood. Metadata is often summarized in a data specification document or a text file.

TABLE 6.15
Summary of common remote sensing formats for operational oceanography data

Name	Description	Tools and conversion
netCDF	Network Common Data Form (netCDF) is a common, machine-independent format for representing scientific data.	ArcGIS and MGET Toolbox can be used to download and import netCDF files to ESRI GRID format. Technical information on netCDF: www.unidata.ucar.edu/software/netcdf
HDF	Hierarchical Data Format (HDF) is a common, machine-independent, self-describing format for representing scientific data. Many open source and commercial tools understand HDF.	ArcGIS and MGET Toolbox can be used to download and import netCDF files to ESRI GRID format. ArcGIS has built-in capabilities to import HDF Technical information on HDF: www.hdfgroup.org
GeoTiff	GeoTIFF is a public domain metadata standard that allows georeferencing information to be embedded within a TIFF file, such as projections, coordinate systems, ellipsoids and datums. It provides a TIFF-based interchange format for georeferenced raster imagery.	Most GIS and remote sensing software packages support GeoTIFF. Technical information on GeoTIFF: http://trac.osgeo.org/geotiff

6.9 CASE STUDIES

Four case studies are described below covering applications in aquaculture practice and management and fisheries monitoring and management. These case studies build on the general principles of remote sensing as described in Section 6.2 and strengthen the general examples of applications described in Section 6.4.

6.9.1 Mapping coastal aquaculture and fisheries structures by satellite imaging radar. Case study of the Lingayen Gulf, the Philippines.

Original publication reference: Travaglia, C., Profeti, G., Aguilar-Manjarrez, J. & Lopez, N.A. 2004. Mapping coastal aquaculture and fisheries structures by satellite imaging radar: case study of the Lingayen Gulf, the Philippines. FAO Fisheries Technical Paper No. 459. Rome, FAO. 45 pp. (available at www.fao.org/docrep/007/y5319e/y5319e00.htm).
Spatial tools: Remote sensing.
Main issues addressed: Inventory and monitoring of aquaculture and the environment.
Duration of study: Six months; the study began in 2003 and ended in 2004.
Personnel involved: (i) Remote sensing specialist with a working knowledge of remote sensing applications in fisheries and aquaculture (FAO Remote Sensing Officer); assisted with the design of the study and analyses and managed the project; full time. (ii) Fisheries and aquaculture specialist with a working knowledge of GIS and remote sensing applications (FAO Aquaculture Officer); assisted with the design of the study; part time for the duration. (iii) Digital image processing specialist (consultant and professor); modelling, image processing and analyses; full time. (iv) Philippine aquaculturist who wrote the description of the structures: fish pens, cages and traps and played a key role in ground verification; part time for the duration. (v) Field verification personnel from the Bureau of Fisheries and Aquatic Resources of the Philippines (four staff), full time for short duration. (vi) Advisers at large (four advisers), who provided data and advice from time to time.
Target audience: The study is aimed at the general fisheries and aquaculture public, governmental administrators and planners, and remote sensing and GIS specialists.

Introduction and objectives: Travaglia *et al.* (2004) implemented the study to map coastal fisheries and aquaculture structures by satellite imaging radar in the Lingayen Gulf, the Republic of the Philippines. The objective of this FAO led study was to test, under operational conditions, a methodology for the inventory and monitoring of shrimp farms using radar satellite imagery. Radar data are known to offer unique capabilities for mapping shrimp farms not only for their inherent all-weather capabilities (important in tropical and subtropical areas where cloud cover is frequent), but mainly because of the way radar interacts with pond dykes (Travaglia, Kapetsky and Profeti, 1999). Because pond dykes are distinguishable from surrounding water surfaces and from the much lower dykes surrounding rice paddies and other flooded areas, they can readily be identified.

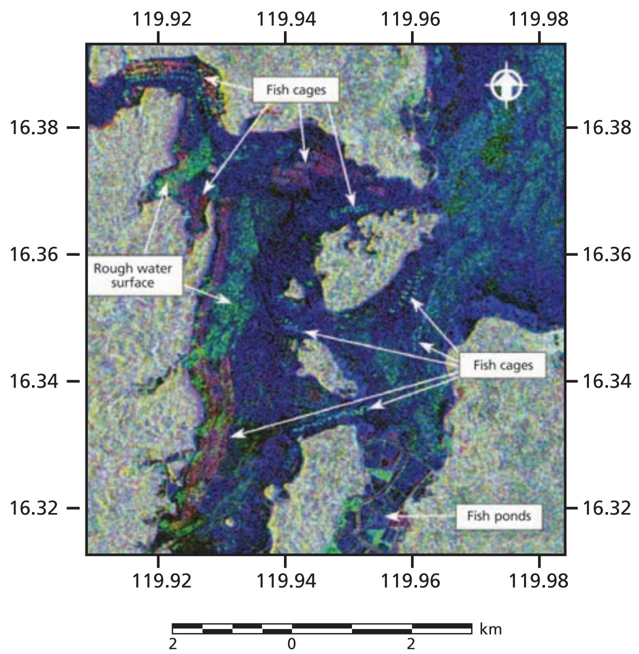
Methods and equipment: The study focused on various types of structures: onshore fish ponds, fish pens in the tidal zone and offshore fish cages and fish traps in the Lingayen Gulf, the Republic of the Philippines, and aimed to compare the suitability of different types of remote sensing imagery. Fish traps are stationary fishing gear with many variations in structural form and materials depending on the target species; in this case, the traps are corrals made from bamboo stakes and other materials that are detectable by radar.

The study area was covered by two ERS-2 SAR images acquired in descending and ascending orbits in December 2002 with a spatial resolution of 25 m (see Box 6.2 for description of satellite orbits). Orbit direction is relevant because it influences the characteristics of the SAR images, and aquaculture features are enhanced in a complementary way. A RADARSAT-1 Fine Mode SAR image was acquired in February 2001 with a ground resolution of 9 m, which covers a smaller area than the ERS images but covered the majority of the area where the aquaculture and fisheries structures are located. The images were geometrically corrected. A fish pond dyke reflects back a large amount of the incident radar energy, but this varies with the angle between the object and the direction of the incident beam. Hence, if a dyke is parallel to the radar beam it may not be detected, which is why ascending and descending orbits were acquired. The other aquaculture and fisheries structures influence the radar signal in a similar way. The vertical sides of fish cages, pens and traps emerging from the water surface, create a corner reflector effect that allows them to be identified.

Classification (feature extraction) was conducted using visual interpretation (as described in Section 6.6.3). This means that a skilled image analyst manually identified and digitized the boundaries of the aquaculture structures. The validation data for an accuracy assessment was collected during field surveys by a team from the Bureau of Fisheries and Aquatic Resources of the Philippines.

Results: The presence of the elevated surrounding dykes ensured straightforward visual interpretation. The area having fish ponds in 2002 was compared with the area mapped in 1977 topographic maps; the comparison indicated that the area had increased by 60 percent, but some of the fish ponds mapped in 1977 had been converted to other uses. Fish cages were detectable in all images, but windy conditions causing rough sea surfaces at the time of image acquisition negatively affected their detectability. Fish cages may be of several shapes (square, rectangular, circular) and made of various materials; those mainly made of metal have a brighter appearance on SAR images, a common detection characteristic in radar technology.

FIGURE 6.10
Interpreted RADARSAT-1 SAR image and the resulting map of the aquaculture and fisheries structures



Source: Travaglia *et al.* (2004).

Fish traps that emerge from the sea surface were separated into two categories: offshore traps and traps inside major rivers. The area occupied by fish traps was calculated to estimate their aerial extent. In many cases, only the central structure of the traps is visible in the images. However, because of their small size, the uncertainty in identification of traps was higher than that of the other structures. An example of the RADARSAT-1 imagery and the classification product of the aquaculture and fisheries structures is provided in Figure 6.10.

Table 6.16 shows the total area covered by the features of interest in the entire study area. This includes various types of aquaculture and fisheries structures, plus the salt pans. The study area completely covers the Pangasinan province, plus approximately two-thirds of La Union and a small portion of Zambales provinces on the island of Luzon. All mapped aquaculture and fisheries structures occur in the Pangasinan province only, with the exception of some fish ponds (90 units covering 18.762 km^2) and of some fish ponds classified as uncertain (13 units covering 2 .613 km^2) existing in the other two provinces. Table 6.17 summarizes the statistics on fish traps. These include all the segments composing the arrow-like traps, if detectable.

TABLE 6.16

Total area covered by the classes of interest (Pangasinan province)

Class description	Number of units	Total area (km^2)
Salt pans 2002	1	4 .156
Fish ponds 2002	587	157 .723
Fish ponds 2002, uncertain[1]	33	2 .036
Fish pens 2001	22	1 .600
Fish cages 2001	105	2 .439
Fish cages, uncertain[2]	7	0.054
Fish cages 2002	267	1 .390
Fish cages 2002, uncertain[2]	16	0.019
Areas with fish traps in the open sea 2001[3]	12	18 .943
Areas with fish traps inside rivers 2001[3]	6	1 .703

[1] Identified in one image only, out of two or three.

[2] Uncertain assignment: may be a small island or a rough patch in the sea surface.

[3] Polygons drawn around the areas on which fish traps were detected to have an estimate of their extension.

Source: Travaglia *et al.* (2004).

TABLE 6.17

Length of the fish traps detected in the study area

Class description	Number of elements	Cumulative length (km)	Average length (km)	Minimum length (km)	Maximum length (km)	Standard deviation
Traps in the open sea	378	50.104	0.133	0.018	0.642	0.093
Traps inside rivers	84	7.886	0.094	0.024	0.364	0.061

Source: Travaglia *et al.* (2004).

The accuracy of the visual interpretation procedure was close to 100 percent for all structures except for fish cages and fish traps, as they may have been moved in the time interval between the image acquisition and the field verification. The clear appearance of fish cages in the SAR imagery permitted a 90 percent estimated mapping accuracy. Mapping accuracy for fish traps was estimated at 70 percent of fish traps that had potential to be detected by remote sensing.

Discussion and recommendations: RADARSAT fine mode imagery provided the best "detectability"for all aquaculture and fisheries structures considered in this study and, therefore, allowed them to be inventoried and monitored with greater accuracy. ERS imagery enabled successful mapping of fish ponds and fish cages but failed to map fish pens and fish traps. For mapping fish ponds and fish cages, using images from ascending and descending orbits acquired within a limited time interval is recommended.

Since the study, there has been significant development in imaging radar as described in this chapter, especially the new high resolution sensors and multi-polarization sensors. The potential for mussel line and fish cage mapping using RADARSAT-2 was clearly demonstrated by Dean *et al.* (2007), but for most developing countries ALOS PALSAR offers the most cost-effective option for imagery with resolution close to RADARSAT-1.

6.9.2 Ocean monitoring in Chile for harmful algal bloom mitigation

Authors: Alan Stockwell, Thomas Boivin, Cristian Puga, Jason Suwala, Erin Johnston, Philippe Garnesson and Antoine Mangin.
Original publication reference: This work is not derived from a peer reviewed or conference publication. The work was delivered as internal ESA reports and to clients and/or users.
Publication/date: Environmental information system for harmful algal bloom monitoring in Chile, using earth observation, a hydrodynamic model and in situ monitoring data. January 2006.
Spatial tools: Ocean colour satellite imagery, hydrodynamic model, web development
Main issues addressed: Harmful algal blooms and aquaculture.
Duration of study: 1 year (January 2005 to February 2006).
Personnel involved: Thomas Boivin, Alan Stockwell, Cristian Puga, Jason Suwala, Erin Johnston, Antoine Mangin, Philippe Garnesson and Loredana Apolloni.
Target audience: Marine aquaculture industry.

Introduction and objectives: Hatfield Consultants (Hatfield), in collaboration with ACRI-ST and Apolloni Virtual Studios (AVS), collaborated on a project called "Integrating Earth Observation into Aquaculture Facilities Monitoring in Southern Chile", also referred to as the "Chile Aquaculture Project" (CAP). The CAP project was funded by ESA and conducted with Mainstream Chile, part of the Norwegian holding company CERMAQ, a world leader in salmon production.

The objective was to demonstrate integrated application of remote sensing data and modelling to provide advanced warning of potentially harmful algal blooms (HAB) so that their impacts can be minimized by the aquaculture industry. The monitoring of the emergence and movement of HABs can provide sufficient time for mitigation measures to be taken by farmers to help reduce potential losses. Long-term data can help improve the site selection process for new facilities.

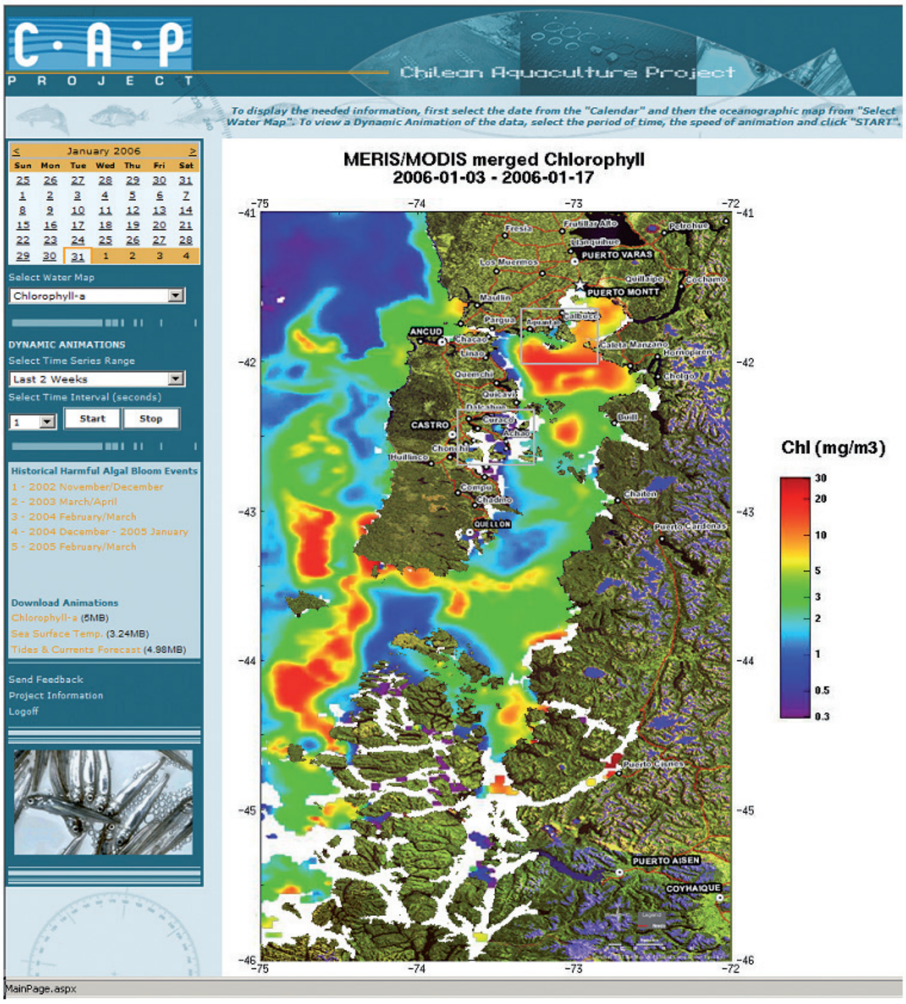
Methods and equipment: To develop a prototype of a HAB warning system, several information sources were used:

- Remote sensing products were provided by ACRI-ST. Chlorophyll-*a* concentration and Secchi depth transparency maps were generated on a daily basis from merged MERIS and MODIS data. Daily SST data were acquired from MODIS with in situ data from buoys.
- *In situ* environmental data were provided by Mainstream Chile.
- Oceanographic, meteorological and land GIS data were collected by Hatfield.

Using these inputs, an oceanographic currents and tidal model was developed, which in combination with transparency and chlorophyll-*a* products, was the basis for development of a HAB risk/warning map. The combination of ocean colour data from different sensors and daily SST meant that product delivery was possible on a daily basis, dependent on cloud cover.

Results: The image processing system and modelling were integrated to produce automatic products of chlorophyll-*a*, SST and Secchi depth. The products were integrated with a GIS to build easy-to-interpret maps, which along with tabular data, were also displayed via a Web portal that was updated each day. The end user could choose the level of detail required by selecting overview maps of the aquaculture production area (e.g. Chiloe Island area) or by selecting specific salmon farm sites to analyse available data. An example of the Web portal page is provided in Figure 6.11, which shows an overview map with a 15-day average of chlorophyll-*a* concentration.

FIGURE 6.11
Chile Aquaculture Project Web portal – main page



Source: Hatfield Consultants (2009).

Validation using in situ and other data enabled accuracies to be estimated as follows:

- Chlorophyll-*a*: within 15 percent;
- SST: within 0.5 °C;
- Secchi depth: ± 2 m (after algorithm recalibration);
- Tide elevation from model: 10 cm at the Puerto Montt control point (astronomical tides);
- Surface current: estimated to be within 1 m/s (but with few means of validation).

Discussion and recommendations: According to the needs of users and the state of the technology, the main focus for HAB warning is on the delivery of chlorophyll-*a* data and on Secchi depths (SST is obviously of importance as well to support modelling). Based on the CAP experience, there was a need for improvements in the accuracy and quantification of the error for the products. Secchi depths should be within an error of 2 metres (± 1 m).

In addition to HAB warnings, another recommendation was exploitation of available ocean colour remote sensing data to derive maps of statistics of chlorophyll-*a* persistence, variability and other statistical parameters at high resolution (e.g. 1 km spatial resolution). This type of climatology information is extremely valuable for site selection for aquaculture production areas. Also, to improve the understanding of the evolution of the environmental parameters, automatic procedures could strongly benefit the system, for example, chlorophyll-*a* front extraction by local gradient computations and quantification of differences between one daily image and the previous images.

Finally, for users there is a real need for derivation of a synthetic "HAB index" that includes all relevant environmental components. This synthetic HAB index could be expressed in the form of a very simple graphic (ideally three colours from green to red, meaning non-risk to high risk).

The CAP project provided important information on HAB occurrences in the key aquaculture regions of Southern Chile, which proved to be extremely valuable to the industry and local government. Long-term monitoring of HAB information is important to help protect the aquaculture industry from possible losses in production, which can be significant in the event of a major HAB event.

6.9.3 Use of SPOT 5 for mapping seagrasses (*Posidonia oceanica*)

Original publication reference: Pasqualini, V., Pergent-Martinia, C., Pergenta, G., Agreila, M., Skoufasb, G., Sourbesc, L. & Tsirikad, A. 2005. Use of SPOT 5 for mapping seagrasses: an application to *Posidonia oceanica*. Remote Sensing of Environment. Vol. 94: 39–45.
Spatial tools: SPOT 5 multispectral imagery, GIS.
Main issues addressed: Environmental impacts of aquaculture; management of aquaculture together with fisheries.
Duration of study: Not reported.
Personnel involved: Not described.
Target audience: Coastal management community.

Introduction and objectives: *Posidonia oceanica* is the dominant seagrass in the Mediterranean Sea (Marba *et al.*, 1996). *P. oceanica* plays an important role in many coastal processes, contributing to sediment deposition and stabilization and to attenuating currents and wave energy (Fornes *et al.*, 2006). Seagrass meadows are also considered to be among the most productive ecosystems, supporting diverse flora and fauna and providing nursery and breeding grounds for many marine organisms (Francour, 1997; Hemminga and Duarte, 2000). *P. oceanica* is a slow-growing climax species that forms large stable meadows, but there is evidence of decline in many areas as a result of warming sea temperatures and pollution (Marba *et al.*, 1996, Holmera *et al.*, 2008, Marba and Duarte, 2010)

Potential sites for coastal aquaculture, if utilized, may affect ecologically sensitive areas such as coral reefs and seagrass beds, and off-the-coast and offshore sites may still need to consider potential impacts on sensitive areas such as *P. oceanica* meadows and apply the precautionary principle. Maps of the distribution of *P. oceanica* are required for effective management and conservation.

A wide range of methods may be used for mapping seagrasses (McKenzie, Finkbeiner and Kirkman, 2003), including optical satellite and aerial remote sensing and acoustic sampling. Generally, the key challenges for mapping *P. oceanica* using optical images are: (i) limited light penetration to the maximum depth of *P. oceanica* distribution (about 40 m); and (ii) spatial resolution of the sensor in relation to the potential patchy distribution of *P. oceanica* with substrates such as rock and sand. Aerial photographs (Pasqualini *et al.*, 1998, 2005), Compact Airborne Spectrographic Imager (CASI) (Mumby and Edwards, 2002) and Ikonos imagery have been employed (Fornes *et al.*, 2006) in recent studies to map seagrasses.

Pasqualini *et al.* (2005) investigated the potential of SPOT 5 optical satellite imagery for mapping *P. oceanica* in Zakynthos Marine National Park (Mediterranean Sea, Greece). The objective of the study was to examine the potential of different spatial resolution SPOT 5 images to map seagrass. The bay is 12 km long by 6 km wide with seagrass known to range from the near surface to approximately 30 m depth. Four types of community and seabed type are found: mobile sediments (silts and sands), communities on hard substrates (including shingle), continuous beds of *P. oceanica* and mosaics of beds (on a mat, rock or sand).

Data: SPOT 5 imagery has four spectral bands: green (0.50–0.59 μm); red (0.61–0.68 μm); near infrared (0.78–0.89 μm); and mid-infrared (1.58–1.75 μm). The first three bands have a spatial resolution of 10 m while the mid-infrared has a resolution of 20 m. Combination of multiple SPOT 5 images acquired at the time also provides multispectral imagery enhanced to 2.5 m spatial resolution. Because there is little penetration of longer infrared wavelengths through the water column, only the green and red visible bands were used at 10 m and 2.5 m resolution in a SPOT 5 imagery acquired on 1 September 2003.

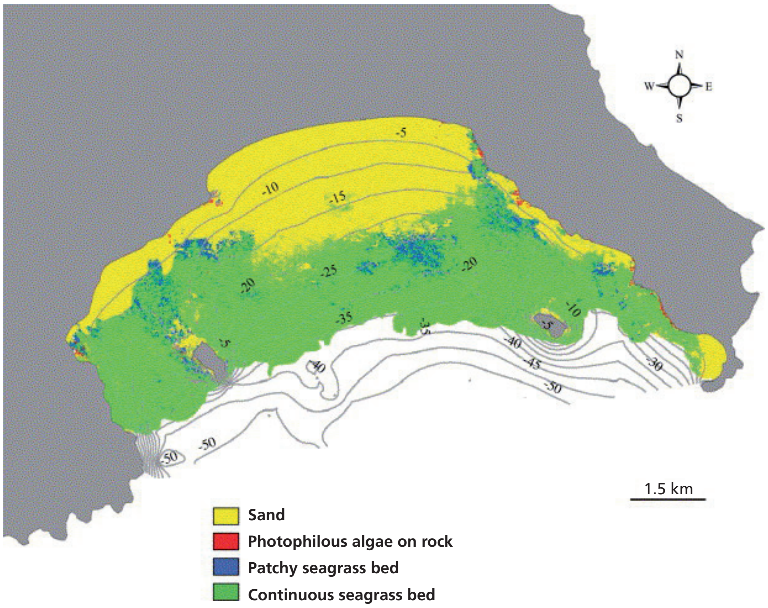
Methods: Processing of the two SPOT images was carried out using Multiscope software (Matra Systems and Information). The terrestrial part was masked in order to optimize the distinction between communities and types of seabed in the marine part. Principal Component Analysis (PCA) was applied to the two bands in each image. A supervised classification was then applied separately to the depth layers 0–10 m and 10–20 m so as to minimize any confusion between classes due to depth. This technique was previously applied on aerial photographs (Pasqualini *et al.*, 1997) and caution is required because it can result in classification bias near the depth limit boundary.

Classification training data were 189 field observations points obtained by scuba diving or observing the seabed from a boat. These data enabled the communities and types of seabed in Laganas Bay, Greece, to be identified. The accuracy of the habitat maps was determined using the overall accuracy. Subsequently, some manual corrections were made, for example, masking beyond the maximum possible depth of *P. oceanica* beds.

Outputs: The classification results revealed the predominance of *P. oceanica* beds in the bay, from the surface down to a depth of about 30 m. The map at 10 m resolution is shown in Figure 6.12 – a large area of sand occupied the northeast of the bay down to a depth of 20 m, while the southeast and northwest were occupied by large rocky slabs, colonized by photophilous algae. These rock-dwelling photophilous algae were absent beyond the 10 m isobath. On the maps with a resolution of 2.5 m, substantial areas of patchy seagrass beds were identified over the whole of the depth range studied.

The overall accuracy of the habitat maps ranged from 73 to 96 percent. The 10 m image provided a better overall accuracy for each depth band. Sand was mapped least accurately. The patchy seagrass beds were mapped with a higher degree of accuracy using the 2.5 m resolution SPOT images because their improved spatial resolution compared to the other images revealed the patchiness of the habitat.

FIGURE 6.12
Main benthic assemblages and bottom types at Laganas Bay, Greece, based on classification of a SPOT image (10 m resolution)



Source: Pasqualini *et al.* (2005).

In summary, SPOT image classification was considered a valuable method for a rapid identification of seabed types. The large image size of SPOT 5 makes it an attractive tool for the management of coastal waters; however, SPOT 5 and several other sensors lack a blue spectral band. Since the study by Pasqualini *et al.* (2005), WorldView-2 was launched in 2009 with a 1.8 m resolution visible spectrum "coastal band" (400–450 nm) that penetrates the water to greater depth. This sensor offers potential for improved and detailed mapping of *P. oceanica* beds. In general, satellite-based methods offer most potential in shallow waters where significant *P. oceanica* losses caused by human impact are expected to occur. The use of remote sensing, coupled with GIS, could be of immense value to supporting improved coastal management decisions and in EIA for assessing the potential impacts of aquaculture on coastal environments on *P. oceanica* meadows.

6.9.4 Fishing ground forecasts in Japan

Original publication reference: Saitoh, S.-I., Mugo, R., Radiarta, I.N., Asaga, S., Takahashi, F., Hirawake, T., Ishikawa, Y., Awaji, T. In T. & S. Shima. 2011. Some operational uses of satellite remote sensing and marine GIS for sustainable fisheries and aquaculture. ICES Journal of Marine Science, 68(4): 687–695.
Publication/date: 2007, 2009 and 2011.
Spatial tools: Remote sensing and satellite communication systems.
Main issues addressed: Fisheries management systems.
Duration of study: Multiple years.
Personnel involved: Researchers and developers from a research centre, two private companies and a regional local development agency.
Target audience: Fishers, fisheries and resource managers, fisheries researchers.

Introduction: The Traceable and Operational Resource and Environment Data Acquisition System (TOREDAS) provides fishing ground forecasts for Japanese common squid (Todarodes pacificus), Pacific saury (Cololabis saira), skipjack tuna (Katsuwonus Pelamis) and albacore tuna (Thunnus alalunga). TOREDAS aims to promote sustainable fisheries operation and management in the offshore zone around Japan.

Satellite-derived temperature and productivity data are used to identify areas where fish and squid tend to aggregate for feeding. TOREDAS delivers prediction of potential fishing zones in near real-time to fishing vessels via Internet and satellite connection. Users can generate products dynamically, such as overlaying maps, and measuring the distance from the nearest port or fishing ground (Kiyofuji *et al.*, 2007).

Methods and equipment: TOREDAS has four components: (i) data acquisition system; (ii) database; (iii) analysis module; and (iv) Internet and on board GIS. Chlorophyll-*a* concentrations are derived from MODIS and SST are processed in near real-time at 1-km resolution and sent to the database server via file transfer protocol (FTP). Data analysis is performed using commercial image processing software to extract and calculate contours, gradients and anomalies in the oceanographic data that indicate potential fishing grounds. ArcGIS software is used for analysis and GEOBASE software development platform is used for mapping on board the vessels.

TOREDAS also integrates data on vessel locations using a high-resolution vessel monitoring system (VMS) (Saitoh *et al.*, 2011). Using the VMS data, TOREDAS is able to measure the distance and speed of vessels and to categorize vessel activity. This type of information can improve operational fishery management and fishing effort control. TOREDAS products have a hierarchical structure defined as from Level 1 to Level 5[171]:

- Level 1 products are raster images of SST and chlorophyll-*a* concentrations.
- Level 2 products are obtained by image analysis to extract gradients, fronts or anomalies in the SST and chlorophyll-*a* concentration.
- Level 3 products are overlays of Level 1 and Level 2 data.
- Level 4 products comprise fishing ground areas estimated from algorithms using Level 3 results as inputs.
- Level 5 products are a one- or two-day forward prediction of fishing ground formation.

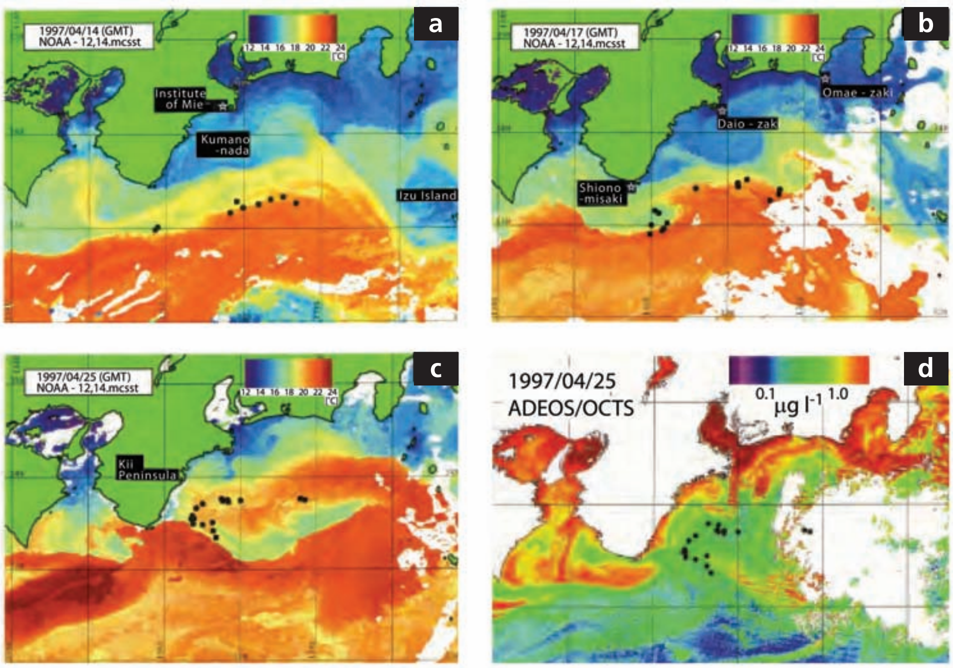
These processing of data into the product levels described above is automatic so that the fishers can receive information in near real-time.

[171] Note this is different from data levels that are often defined by international space agencies.

Results: An example of the research and development of fishing ground predictions for the southeast coast of Honshu Island, Japan, is described by Saitoh *et al.* (2009, 2011). AVHRR data from NOAA were received and processed into SST maps; chlorophyll-*a* concentration maps were obtained from the OCTS and SeaWiFS sensors. For validation, satellite SST and chlorophyll-*a* data were compared with in situ measurements of temperature recorded by the fishing boats and chlorophyll-*a* concentrations. Figure 6.13 shows the SST and chlorophyll-*a* concentration products. In Figure 6.13 (a) to (c), the SST over a period of ten days is shown, and the warm Kuroshio Current (red) and cold coastal waters (blue) are clearly visible. Figure 6.13 (d) shows the chlorophyll-*a* image for the same date as the SST data in Figure 6.13 (c).

Skipjack fishing vessels are shown as black dots in the images and are located along the edges of the ocean colour front between the coastal and offshore waters. Optimal fishing grounds were concentrated in the Kuroshio waters near the ocean colour front, with chlorophyll-*a* concentrations ranging from 0.2 to 0.5 µg.l^{-1}. The potential skipjack tuna fishing grounds and the effectiveness of using SST data for predicting fishing grounds is apparent. Ocean colour data are also important for identification of fishing grounds, especially when strong summer solar radiation heats up the surface layer of the ocean, rendering the SST data less effective.

FIGURE 6.13
Sea surface temperature and chlorophyll-*a* concentrations for the southeast coast of Honshu Island, Japan



Note: Black dots represent the trolling-line skipjack fishing grounds

Source: Saitoh *et al.* (2009).

Discussion: The TOREDAS system provides operational fishing ground forecasts and can support improved fishery management. Although the system could contribute to greater catching power, under sustainable fisheries management regulations it should be seen as a management tool to help monitor activities and improve fisheries economics. Thus, the benefits of TOREDAS include improving the understanding of fishing ground formation and fish migration, contributing to reduced fuel consumption and time spent searching for suitable fishing areas, reducing input costs and improving energy efficiency.

The use of VMS and remote sensing information together can provide a detailed account of the activities of fishing vessels. VMS can also aid in fine-tuning fishery forecasting models by including information on how fishing vessel skippers select fishing grounds relative to remotely sensed oceanographic data. Another potential application is as an educational tool for transferring fishing skills and knowledge from experienced to new captains (Saitoh *et al.*, 2011). In 2006, TOREDAS was handed over to a company called SpaceFish LLP.

6.10 CONCLUSIONS

Advances in remote sensing systems, communications technology and computer processing mean that remote sensing data are now much more accessible. Many former impediments preventing applications of remote sensing within GIS for aquaculture and fisheries may no longer apply, including affordability, information content, timeliness and revisit frequency. Many remaining challenges are more related to lack of awareness, poor management and a lack of training and support, plus the necessary expertise to integrate different data sets (imagery) within GIS or other information systems. However, because of the efforts of several international organizations, including FAO, the European Space Agency and IOCCG, there are many well-documented applications of remote sensing for fisheries and aquaculture and opportunities for GIS specialists to access new and important sources of data.

This chapter has recommended reviewing optical satellite sensors by considering the information that the user wants to obtain; for example, ocean colour, SST, or land cover and coastal zone mapping. Some sensors were designed for specific applications, such as global ocean colour monitoring, but most have several potential applications including deriving information for ocean, coastal and land areas. Optical data are affected by cloud cover, which can limit the available time series, revisit frequency and timeliness of data acquisition. However, there are an increasing number of options for optical data acquisition, and relatively high spatial resolution optical data are becoming available at lower costs. Radar offers the advantage that they are not affected by cloud cover and they can provide different and complementary information to optical remote sensing systems. An increasing range of imaging radar sensors are available and provide a range of spatial resolutions, wavelengths and polarizations. The accessibility and cost of data varies, and some countries have more cost-effective access to radar data through national ground receiving stations and agreements with commercial operators. There are often good time series of radar imagery, and the potential for fast acquisition and delivery of new data is a key advantage of radar. In the future, continuity of radar is assured and the cost of data access looks set to decrease significantly.

Fisheries and aquaculture are practiced worldwide in vastly variable environments and at greatly varying scales, but the biological systems and sustainable human exploitation are controlled to a greater or lesser extent by many variables that can be measured by remote sensing. It is likely that remote sensing will play an ever more important role in monitoring, planning and management activities, especially given the large proportion of the earth's surface that is covered by aquatic environments and the costs that would be involved in collecting data requirements by other means. The unique capability of satellite remote sensing to provide regular, repeated observations of the entire globe or specific regions at different spatial scales is also increasingly important in the context of global climate change. The time series of information products that are operationally derived from remote sensing should be part of government assessments of climate change impacts and action plans for industry adaptation.