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# Satellite Remote Sensing for Coastal Management: A Review of Successful Applications

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**Abstract** Management of coastal and marine natural resources presents a number of challenges as a growing global population and a changing climate require us to find better strategies to conserve the resources on which our health, economy, and overall well-being depend. To evaluate the status and trends in changing coastal resources over larger areas, managers in government agencies and private stakeholders around the world have increasingly turned to remote sensing technologies. A surge in collaborative and innovative efforts between resource managers, academic researchers, and industry partners is becoming increasingly vital to keep pace with evolving changes of our natural resources. Synoptic capabilities of remote sensing techniques allow assessments that are impossible to do with traditional methods. Sixty years of remote sensing research have paved the way for resource management applications, but uncertainties regarding the use of this technology have hampered its use in management fields. Here we review examples of remote sensing applications in the sectors of coral reefs, wetlands, water quality, public health, and fisheries and aquaculture that have successfully contributed to management and decision-making goals.

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## Introduction

As of 2010, over 2.5 billion people (~40% of the global population) live in coastal ecosystems that are increasingly vulnerable to natural and anthropogenic influences (Sale et al. 2014). In the next few decades, these areas will be affected by changing atmospheric and ocean temperatures, sea levels, ocean chemistry, weather patterns, and the increased demands of a growing global population. Without proper strategies to manage our use of resources, these changes will result in increased risks to human health, property, economic vitality, and further damage to services we derive from these ecosystems (Pereira et al. 2010; Pettorelli et al. 2014; Sale et al. 2014; Wigbels 2011). To improve coastal ecosystem management, decision-makers should take further advantage of the synoptic, frequently sampled, and often freely accessible satellite remote sensing technology that is available today (Kachelreiss et al. 2014; Pettorelli et al. 2012).

Remote sensing techniques have substantially improved our ability to observe the environment and its processes (De La Rocque et al. 2004; Heumann 2011). Currently, however, remote sensing technologies are underutilized in environmental management (Heumann 2011; Pettorelli et al. 2014). Based on an internal survey of Environmental Protection Agency personnel, who were responsible for integrating scientific research into decisions related to policy and management, Schaeffer et al. (2013) identified four main themes regarding why these technologies may be underutilized: costs and accuracy of data products, uncertainty about satellite mission continuity, and difficulty in obtaining administrative approval for using remote sensing in decision-making. Additionally, managers may be unfamiliar with the breadth of current satellite data, and therefore under the impression that available imagery may be insufficient to meet their needs.

Our goal with this review is to illustrate applications of satellite remote sensing techniques that have successfully improved management capabilities in coastal sectors, and summarize the data that is currently available for management use. We provide examples in coral reefs and wetlands, assessments of water quality and public health, and support to fisheries and aquaculture activities.

Each satellite sensor is designed for particular sets of applications. Trade-offs exist between spectral, spatial, and temporal resolution for different sensors. Specifically, spatial resolution is the spatial “footprint”, or pixel (picture element) size, which is the smallest portion of the Earth’s surface discretely sampled by a device. Figure 1 compares the spatial resolution of the Landsat 8 sensor (30 meter) to that of WorldView-2 (2 meter), as well as the additional trade-off of greater geographical coverage per image “tile” with coarser resolution imagery. Spectral resolution is the smallest window in wavelength or frequency space of the electromagnetic spectrum that is discretely sampled by a sensor. Sensors typically have several spectral bands that sample different parts of the electromagnetic spectrum at different spectral resolutions. Temporal resolution is the frequency or revisit time at which a sensor collects subsequent measurements of the same location. In addition, sensors and the satellite platforms on which they fly need to be designed to satisfy a number of minimum requirements in order to observe particular phenomena.

For example, many satellite sensors designed for viewing the ocean in the visible range of the electromagnetic spectrum (reflected color) and in the infrared (emitted thermal radiation) have nominal spatial resolutions of about one square kilometer. This allows capturing mesoscale and larger spatial variability of the open ocean at near daily

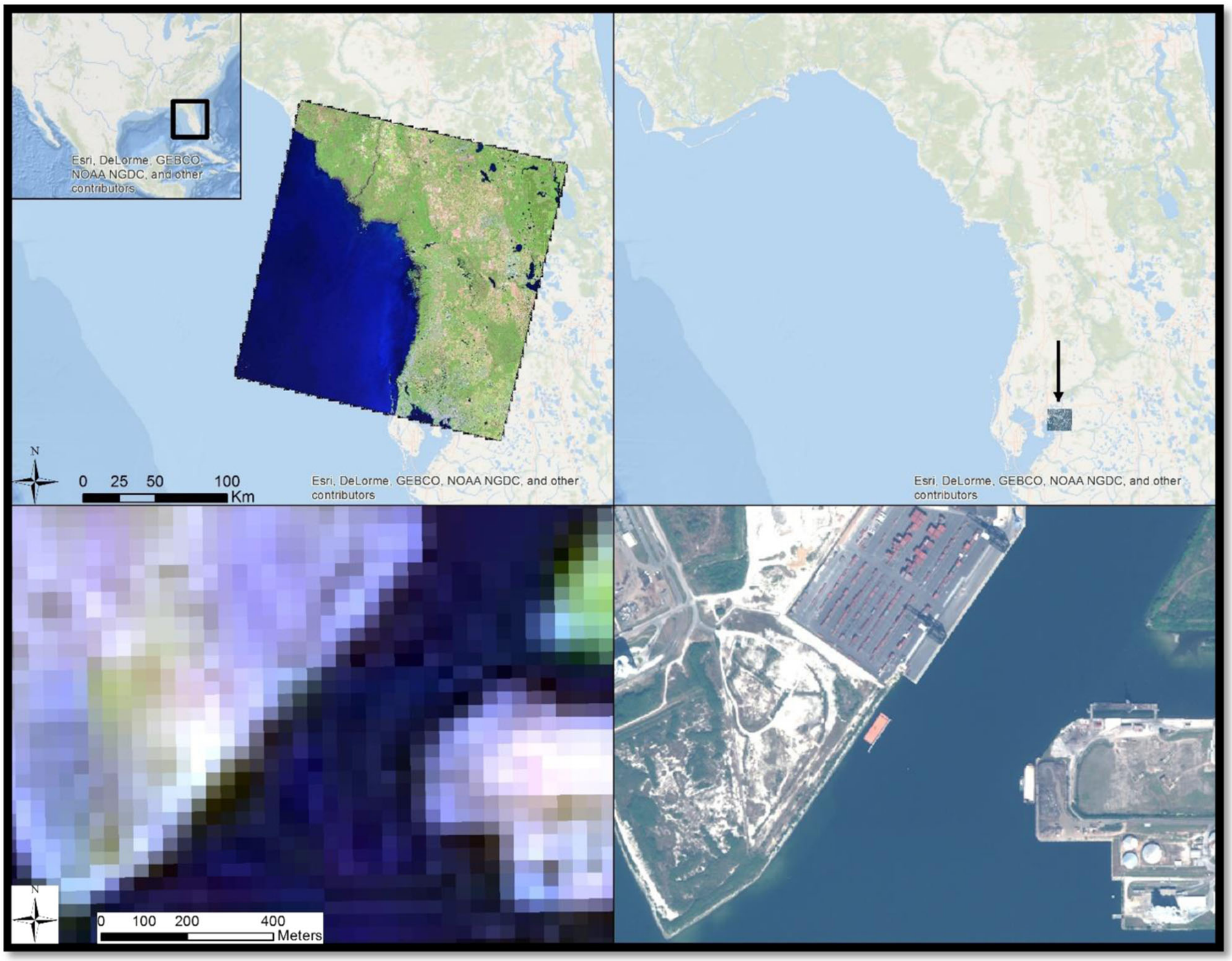


**Fig. 1** Geographic coverage per image “tile” (*top*), and spatial resolution (*bottom*) of Landsat 8 (*left*) and WorldView-2 (*right*) are compared

revisit time from orbits at altitudes of about 600–800 km above the Earth. Medium-resolution sensors such as those flown on the Landsat series have a spatial resolution on the order of 30 m, wide spectral bands (~60 nm bandwidth), and a revisit time of 16 days. The European Sentinel-2 satellite has a spatial resolution from ~10 to 60 m depending on the band, spectral bandwidths from 10 to 60 nm, and a revisit period of ~2–3 days. Geostationary sensors operate from an orbit of about 36,000 km above the Earth and can collect data several times per day from low-latitudes to mid-latitudes in a single hemisphere. Many weather satellites have such hemispheric coverage. The Korean Geostationary Ocean Color Imager (GOCI) focuses on a small geographic area with a spatial resolution of ~ 500 m. Satellite sensors such as these will be discussed in the following management sectors for which they are most applicable. Table 1 summarizes the sensors mentioned here by resolutions, years of available data, relevant management uses, and locations from which data may be downloaded or requested.

## Management Sectors

### Coral Reefs

Shallow-water tropical coral reefs are some of the most diverse and productive ecosystems in the ocean (Bellwood and Hughes 2001; Small et al. 1998). Globally, the economic value of reefs is ~US $30 billion annually (Chen et al. 2015). They are critical for the social and economic well-being of people living in coastal regions as they provide seafood, pharmaceuticals, recreation, and coastal protection (Burke et al. 2011). Despite these ecological and social benefits, coral reefs are undergoing major habitat loss (Baker et al. 2008; Gardner et al. 2003).

The progressive warming of global sea surface temperature (SST) is one of the most important environmental stressors responsible for decline in coral cover (Chollett et al. 2012; Eakin et al. 2010; Hoegh-Guldberg and Bruno 2010; Kleypas et al. 1999; Soto Ramos et al. 2011). Widespread coral bleaching and mortality are linked to anomalously warm water driven by El Niño Southern Oscillation events (Baker et al. 2008; Goreau et al. 2000; Goreau and Hayes 1994). Reductions in coral cover of key reef-building species is changing the biodiversity in these ecosystems, and reducing critical habitat for many marine species including reef fishes (Goreau et al. 2000; Somerfield et al. 2008; Soto Ramos et al. 2011; Vega-Rodriguez et al. 2015). Thus, loss of reef services (e.g., tourism and recreational activities) due to decreased coral cover and biodiversity has been estimated to be approximately US $4–$24 billion annually (Chen et al. 2015).

Building stronger coral reef management strategies requires identifying regional stressors (e.g., SST, decreased water quality due to coastal erosion or runoff) and evaluating them in the context of species-specific responses and reef connectivity (Aswani et al. 2015). Satellite-based observations have successfully provided inexpensive real-time data used to enhance our understanding of coral reef dynamics. Extensive reviews cover remote sensing methods and applications for coral reef observations and monitoring (Eakin et al. 2010; Goodman et al. 2013; Hedley et al. 2016; Hochberg 2011). Specifically, satellite-derived products have been used to monitor and forecast global coral bleaching and mortality, map global distributions of coral reef habitats, provide synoptic views of large-scale oceanographic processes, and evaluate changes in water quality.

#### *Management applications*

Satellite observations, combined with local in situ time series of bio-geochemical observations and forecasting models, are required for better support of ecosystem based

Management (EBM) initiatives (IOCCG 2009; Lorenzoni and Benway 2013; Sherman et al. 2011; Stuart et al. 2011). For example, newly derived thermal stress products (e.g., bleaching alert areas; Fig. 2) were developed by the National Oceanic and Atmospheric Administration (NOAA) Coral Reef Watch Program (Liu et al. 2014) in response to coastal and reef manager needs. NOAA's next-generation of daily global geostationary and polar-orbiting SST images reliably monitor thermal-stress conditions on 95% of reefs worldwide (Liu et al. 2014). These operational and freely accessible products have been incorporated into the monitoring and management efforts of the NOAA Coral Reef Conservation Program, the states of Florida and Hawaii, The Nature Conservancy, Guam, and the Commonwealth of the Northern Mariana Islands, among others (Liu et al. 2014). In the Florida Keys, these products are frequently used as part of the Coral Bleaching Early Warning Network conditions reports (Walter 2015). Based on satellite SST products, prediction-based models have been integrated within early warning systems in Australia and are used to understand and target increased incidence of coral disease outbreaks (Maynard et al. 2011). These models, combined with volunteer-based ground-truth monitoring networks, help management responses to succeed. Additionally, acute changes in the coastal water quality that surrounds coral reefs could potentially alter reef health. The impact of sediment plumes, another concern for reef managers, has been associated with increased incidence of coral disease (Pollock et al. 2014). The extent of sediment plumes, caused by dredging activities or river discharge, has been estimated along coastal areas and nearby reefs using freely accessible high spatial-resolution and

**Table 1** Satellite sensors discussed in this review and their specifications

| Sensor | Free to Public? | Spatial resolution | Spectral resolution | Temporal resolution | Years of available data | Management uses | Data source |
|---|---|---|---|---|---|---|---|
| ALOS | Yes | 2.5–10 m | 6 bands: Vis, IR, MW | 46 days | 2006–2011 | Wetlands, aquaculture | https://earth.esa.int/web/guest/home |
| AMSR-E | Yes | 6–75 km | 6 bands: MW | 3 days | 2002–2011 | Public health | https://giovanni.sci.gsfc.nasa.gov/giovanni/ |
| ASAR | Yes | 30 m | 1 band: MW | 35 days | 2002–2012 | Wetlands, aquaculture | https://earth.esa.int/web/guest/home |
| AVHRR series | Yes | 1.1 km | 4–5 bands: Vis, IR | 1 day | 1978–present | Fisheries, aquaculture, corals | https://earth.esa.int/web/guest/home |
| CZCS | Yes | 825 m | 6 bands: Vis, IR | 1 day | 1978–1986 | Fisheries | https://oceancolor.sci.gsfc.nasa.gov/ |
| GOCI | Yes | 500 m | 8 bands: Vis | 8 images per day | 2010–present | Water quality | https://oceancolor.sci.gsfc.nasa.gov/ |
| IKONOS | Some | 1–4 m | 5 bands: Vis, IR | 3 days | 1999–present | Wetlands | https://earth.esa.int/web/guest/home |
| Landsat series | Yes | 15–120 m | Up to 11 bands: Vis, IR | 16–18 days | 1972–present | Wetlands, corals, water quality, aquaculture | https://landsatlook.usgs.gov/ |
| MERIS | Yes | 300 m–1.2 km | 15 bands: Vis, IR | 3 days | 2002–2012 | Wetlands, corals, water quality, aquaculture | https://oceancolor.sci.gsfc.nasa.gov/ |
| Meteosat series | Yes | 1–5 km | Up to 12 bands: Vis, IR | Up to 15 minutes | 1977–present | Fisheries | http://www.eumetsat.int/website/home/Data/index.html |
| MODIS | Yes | 250 m–1 km | 36 bands: Vis, IR | 1–2 days | 2000–present | Corals, water quality, aquaculture | https://giovanni.sci.gsfc.nasa.gov/giovanni/ |
| OMI | Yes | 24 km | 740 bands: Vis, UV | 1 day | 2004–present | Public health | https://giovanni.sci.gsfc.nasa.gov/giovanni/ |
| QuickBird | Some | 0.6–2.9 m | 5 bands: Vis, IR | 1–3 days | 2001–present | Wetlands | https://earth.esa.int/web/guest/home |
| SeaWiFS | Yes | 1 km | 8 bands: Vis | 1 day | 1997–2010 | Water quality, public health, aquaculture | https://giovanni.sci.gsfc.nasa.gov/giovanni/ |
| Sentinel–2 | Yes | 10–60 m | 13 bands: Vis, IR | 5 days | 2015–present | Wetlands | https://earth.esa.int/web/guest/home |
| SSMI | Yes | 15–69 km | 4 bands: MW | 1 day | 1987–present | Aquaculture | http://www.remss.com/missions/ssmi |
| SPOT-5 | No | 2.5–20 m | 5 bands: Vis, IR | 2–3 days | 2002–2015 | Wetlands, aquaculture | https://www.spot-take5.org/client/#/home |
| WorldView-2 | Some | 0.5–2 m | 9 bands: Vis, IR | 1–3 days | 2009–present | Wetlands | https://earth.esa.int/web/guest/home |

*Note*: Some data sources require user registration or additional criteria

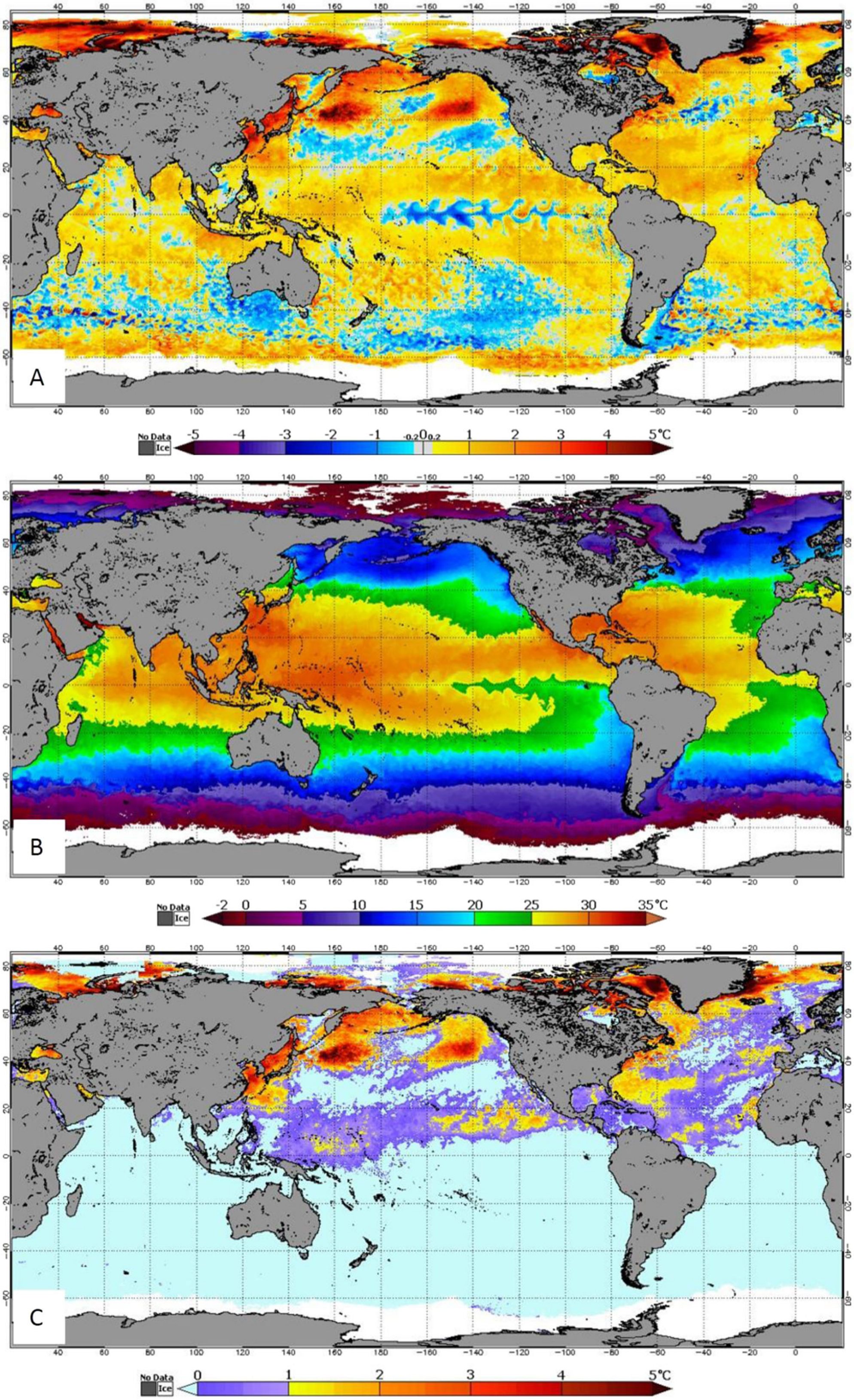


**Fig. 2** NOAA Coral Reef Watch 5-km spatial-resolution thermal-stress products for August 22, 2016: **a** SST anomaly, **b** SST, and **c** Coral Bleaching Hot Spots (https://coralreefwatch.noaa.gov/satellite/index.php)

temporal-resolution remote sensing data from sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS) and Landsat (Barnes et al. 2015; Evans et al. 2012).

The combination of high spatial-resolution satellite imagery (e.g., IKONOS) with aerial photography and Light Detection And Ranging data, which uses multiple returns of laser surveying to build digital elevation models, has led to the creation of accurate benthic habitat maps for Caribbean reefs, including some endangered stony coral species (e.g., *Acropora spp.*) (Wirt et al. 2015). Researchers at the Florida Fish and Wildlife Commission successfully used these habitat maps to identify the distribution of *A. palmata* and *A. cervicornis* in the Florida and Caribbean regions and to identify areas of suitable substrate for *Acropora* spp. coral larvae settlement (Wirt et al. 2015). Satellite-derived data have also been used to identify and manage marine protected areas, which include important reefs. For example, in Brazil, proxies for habitat quality derived from satellite observations (e.g., thermal stress, sedimentation) combined with high-resolution coral-reef habitat maps derived from Landsat images were used to select priority reef-conservation areas (Magris et al. 2015).

## Wetlands

Global wetlands are estimated to be worth billions of dollars for their ecosystem services (i.e., the direct and indirect contributions of ecosystems to human well-being). These include commercial-fish and recreational-fish habitat and nurseries, nutrient and suspended-solid filtration and removal, flood protection, erosion control, recreation, aesthetics, and other cultural values (Dahl and Stedman 2013; Ozesmi and Bauer 2002; Turner and Gannon 2014). Wetlands are, in fact, the only ecosystem covered by a global treaty—the Ramsar Convention on Wetlands, signed in 1971. Despite their significance, the areal extent of wetlands declined substantially in the 20th century as a result of development, pollution, and sea-level rise, among other contributors (Dahl and Stedman 2013; Raabe et al. 2012).

In response, management agencies around the world have identified wetland restoration and conservation as priority goals, and many have employed remote sensing technologies to help achieve those goals. In fact, the use of aerial-based imagery for wetland management is relatively well-established (see Green et al. 1996 for a review of aerial and early satellite sensor applications). Recent advances, however, in the spatial, spectral, and temporal resolutions of satellite-based sensors, as well as declining costs associated with data acquisition and processing, have increased the viability of satellite sensors as wetland-management tools (see Heumann 2011, for a comprehensive summary of satellite sensors available through 2010 and their applicability for mapping mangroves).

### *Management applications*

The following management needs have been served through remotely sensed data: mapping at site, basin, and global levels; inventory and baseline assessment; status and trends assessment; monitoring and reporting; and management planning and implementation (MacKay et al. 2009). Mapping wetlands is considered “critical for practical management and decision-making purposes” (MacKay et al. 2009), and many studies have employed satellite data for mapping purposes (Giri et al. 2011; Jia et al. 2014; MacAlister and Mahaxay 2009; McCarthy et al. 2015). Using Landsat imagery, MacAlister and Mahaxay (2009) successfully mapped wetlands of the Lower Mekong Basin in Southeast Asia. They identified 31 wetland and 23 non-wetland categories in five pilot study areas. Images were classified using the common Maximum Likelihood approach to a minimum mapping unit of 60 m. Field surveys were used to assess their classification accuracy, which ranged from 77.2–93.8% across the five sites. The maps are now in use for resource and conservation planning at provincial and national levels in the countries of Laos, Cambodia, and Vietnam. They have also been used for Ramsar site delineation, water-use planning, fire and water strategies, and site conservation management plan development (MacAlister and Mahaxay 2009).

Herrero and Castañeda (2009) used Landsat imagery to map, delineate, and monitor wetlands. They evaluated small (<2 to >200 ha) saline wetlands in northeastern Spain with 52 Landsat images from 1984–2004. Unsupervised classification methods were combined with field observations to identify five soil surface covers in each image. These were used to determine the conservation status, limits and functions of 53 wetlands. They found that 60% of the habitats were highly vulnerable to a variety of environmental and anthropogenic stressors, including agricultural intensification, waste dumping, and loss of native vegetation. Landsat imagery proved useful not only for the consistent and comprehensive assessment of wetland conditions, but also for its ability to fill historical gaps of scarce field records (Herrero and Castañeda 2009).

Dabrowska-Zielinska et al. (2009) demonstrated the use of both visible-light and microwave remote sensing data to monitor wetlands. They studied the Biebrza Wetlands in northeastern Poland—a Ramsar test site, and one of the largest wetland ecosystems in Europe. This fragile ecosystem has been intensively drained by development ventures in recent years, but is a target area for restoration and conservation. In order to develop a management strategy, managers needed the remaining wetlands to be mapped, and the marshland habitats characterized. Due to the size, isolation, and challenging terrain, traditional field survey methods were not feasible. The circumstances provided an opportunity for researchers to explore new ways to map wetlands while fulfilling a fundamental wetland-management requirement. Data from multiple microwave-range and visible-range satellite sensors were compared to determine the best vegetation indices for distinguishing marshland vegetation classes remotely. The authors concluded that the Enhanced Vegetation Index (EVI) and Global Environmental Monitoring Index from SPOT VEGETATION, and the EVI from ENVISAT MERIS were most effective in identifying marshland habitat classes. The Leaf Area Index derived from microwave Advanced Synthetic Aperture Radar data was also used for soil moisture estimation, and proved effective even under cloudy conditions when optical data was not useful. The results of this study showed that relatively coarse resolution imagery could be successfully used for identifying and characterizing sufficiently large wetland habitats to be managed, and for monitoring changes in wetland vegetation caused by soil moisture and humidity changes that result from anthropogenic wetland drainage.

## Water Quality

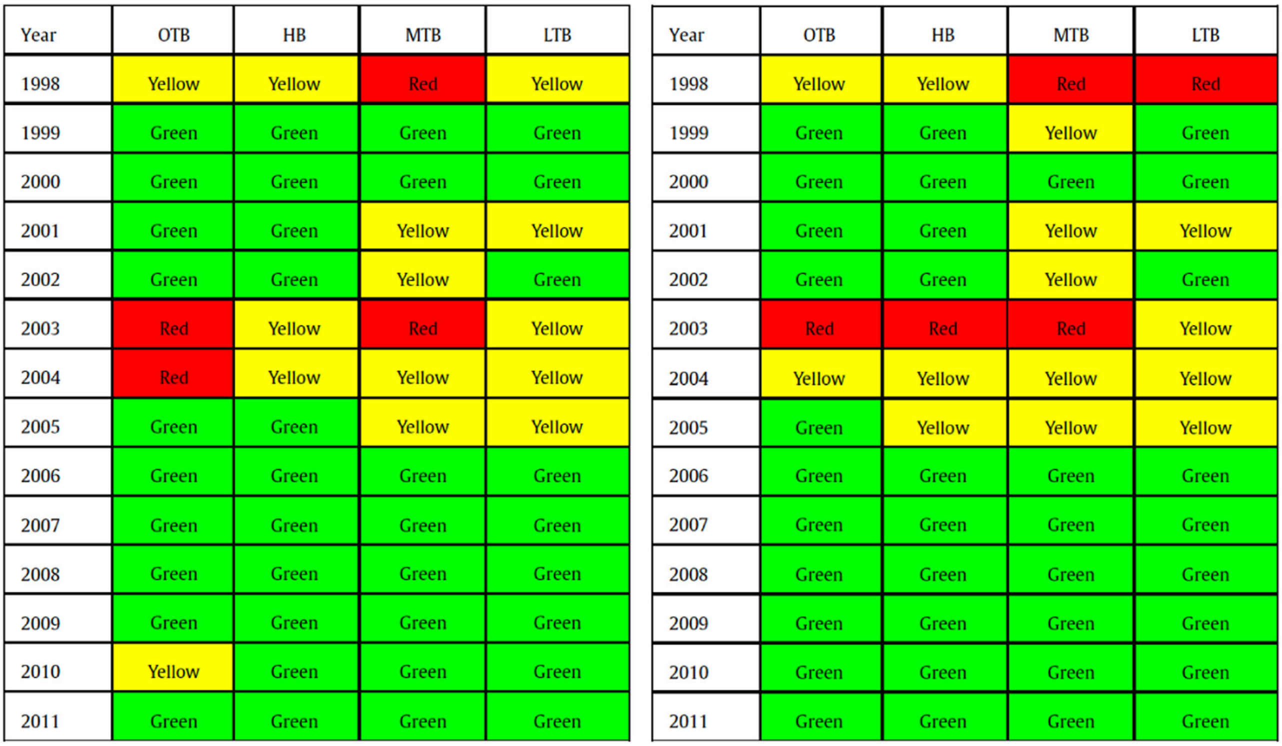
Routine coastal water-quality monitoring is carried out in the field by management agencies but is often costly and labor intensive (Bierman et al. 2011). Due to cost constraints, sampling stations may only represent a small portion of the water body and can only provide a snapshot of water quality conditions in one location at one point in time. Herein, remotely sensed water quality is defined as the simultaneous measurement of three color-producing agents that contribute to the overall “color” of a water body: chlorophyll-a (Chla), suspended minerals, and colored dissolved organic matter (CDOM). These parameters absorb and scatter light in the water column to a degree that can be measured from space (Bukata 2005). They have unique optical signatures in terms of scattering and absorption, which allows for their relative contributions to the overall color of the water to be differentiated. Chla, a proxy for the biomass of algal particles (phytoplankton), is a fundamental parameter in the study of coastal water quality and can indicate increased nutrients in a water body (Bukata 2005; Devlin et al. 2011; Schaeffer et al. 2012). CDOM is defined as the colored portion of the pool of dissolved organic carbon (Blough and Del Vecchio 2002).

Water clarity is another parameter of interest in coastal water-quality management related to light absorption and scattering by mineral particles. Often reported as turbidity or total suspended sediments, water clarity is a measure of reduced light penetration within the water column, which may lead to degraded water quality that can impact the productivity and health of coastal ecosystems (Cloern et al. 2013; May et al. 2003; Wofsy 1983). As an example for Tampa Bay, FL, three constituents (CDOM, turbidity, and Chla) can be simultaneously assessed with the MODIS sensor using the methods of Chen et al. (2007a, b) and Le et al. (2012), respectively. It is important to note that these approaches, particularly for Chla, are quite localized and cannot be broadly applied to a variety of environments.

### *Management applications*

Satellite observations have been used to assess and monitor coastal water-quality in numerous studies. “Black water” events in southwest Florida were observed using MODIS and Sea-viewing Wide Field-of-View Sensor (SeaWiFS) data by Zhao et al. (2013). A study by Thompson et al. (2014) discovered marked seasonal variability in water quality on the Great Barrier Reef in Australia using data from the MODIS sensor. Barnes et al. (2013a) used data from the Landsat and MODIS sensors to investigate historical changes in water quality in the Florida Keys from the 1980’s until present. Using the recently launched GOCI, Jang et al. (2016) developed water quality indices for coastal areas in Korea. The technology exists for the remote sensing community to provide useful, synoptic measurements of relevant water quality indicators to managers (Bukata 2005), but these products are currently underutilized in an operational manner (Schaeffer et al. 2013).

To assist managers in assessing water quality conditions, a decision-support tool for Tampa Bay, Florida was developed by Le et al. (2013) using a satellite-based Water Quality Decision Matrix (WQDM). Based upon previously established targets and thresholds of water clarity and Chla concentration (Janicki et al. 2000), satellite-derived indices of these two parameters were used to create the WQDM, which tracks annual mean water-quality conditions to help inform managers when making decisions. A “*green*” color in the WQDM indicates “good” conditions requiring no direct action by managers. A “*yellow*” color indicates that one of the two water quality indices has exceeded its threshold by more than one standard deviation. *Yellow* conditions indicate that managers should be alert to changing conditions. A “*red*” condition exists if both water quality indices exceed their thresholds by over two standard deviations and indicates poor water quality conditions. If “*red*” conditions persist for two consecutive years, management action is required (Fig. 3). While these WQDM matrices are produced on an annual basis in Tampa Bay Estuary Program reports largely based on in-situ data, satellite-based water quality data that may be used to derive them can be found at the University of South Florida Optical Oceanography



| Year | OTB | HB | MTB | LTB |
|---|---|---|---|---|
| 1998 | Yellow | Yellow | Red | Yellow |
| 1999 | Green | Green | Green | Green |
| 2000 | Green | Green | Green | Green |
| 2001 | Green | Green | Yellow | Yellow |
| 2002 | Green | Green | Yellow | Green |
| 2003 | Red | Yellow | Red | Yellow |
| 2004 | Red | Yellow | Yellow | Yellow |
| 2005 | Green | Green | Yellow | Yellow |
| 2006 | Green | Green | Green | Green |
| 2007 | Green | Green | Green | Green |
| 2008 | Green | Green | Green | Green |
| 2009 | Green | Green | Green | Green |
| 2010 | Yellow | Green | Green | Green |
| 2011 | Green | Green | Green | Green |

| Year | OTB | HB | MTB | LTB |
|---|---|---|---|---|
| 1998 | Yellow | Yellow | Red | Red |
| 1999 | Green | Green | Yellow | Green |
| 2000 | Green | Green | Green | Green |
| 2001 | Green | Green | Yellow | Yellow |
| 2002 | Green | Green | Yellow | Green |
| 2003 | Red | Red | Red | Yellow |
| 2004 | Yellow | Yellow | Yellow | Yellow |
| 2005 | Green | Yellow | Yellow | Yellow |
| 2006 | Green | Green | Green | Green |
| 2007 | Green | Green | Green | Green |
| 2008 | Green | Green | Green | Green |
| 2009 | Green | Green | Green | Green |
| 2010 | Green | Green | Green | Green |
| 2011 | Green | Green | Green | Green |

**Fig. 3** Table 4 from Le et al. (2013) comparing annual mean water-quality conditions in four sections of Tampa Bay, Florida based on indices derived from (*left*) historical field data, and (*right*) satellite data. *OTB* Old Tampa Bay, *HB* Hillsborough Bay, *MTB* Middle Tampa Bay, *LTB* Lower Tampa Bay

Laboratory website (http://optics.marine.usf.edu/projects/vbs.html).

## Public Health

Remote sensing techniques have been widely applied in coastal areas to assess public health concerns (Glasgow et al. 2004; Hay 2011). Global air pollution is one of the most critical environmental health risks, estimated to cost 2 million premature deaths, and it is largely due to enhanced anthropogenic activities such as burning fossil fuels (Wigbels 2011). Global observations of air pollutants such as aerosols, tropospheric ozone, tropospheric nitrogen dioxide, carbon monoxide, formaldehyde, and sulfur dioxide are now widely available (Paciorek and Liu 2009; Wang et al. 2015). Among air pollution variants, airborne dust carrying heavy metals, and particulate matter (PM) is considered one of the most harmful (Yan et al. 2015). Urban air pollution is one of the top 15 causes of death and disease globally, and it is always ranked in the top 10 for high-income countries (Bechle et al. 2013). Reliable predictions of public health risks such as heat waves, extreme and prolonged heat episodes, atmospheric ozone, dust and other aerosols that trigger asthmatic responses are vital to improving public health (Shamir and Georgakakos 2014).

Additionally, vector-borne diseases (VBD) such as those carried by mosquitoes, ticks, and flies are currently responsible for more deaths in humans than all other causes combined (Kalluri et al. 2007). Improved methods are required for forecasting, early warning systems, prevention, and control of VBD due to the increasing trend of large-scale epidemics such as malaria, dengue, and chikungunya (Chuang et al. 2012).

### *Management applications: Air pollution*

Remotely sensed estimations of aerosols could lead to better assessments of air quality, particularly in suburban and rural areas that are often far from in-situ sensors (Basly and Wald 2010; Bechle et al. 2013; Malakar et al. 2014). For example, satellite-based observations of nitrogen dioxide from the Ozone Monitoring Instrument provide reliable measurements of ground-level nitrogen-dioxide exposure within a large area (Bechle et al. 2013). Additionally, researchers at the Hong Kong Polytechnic University used remote sensing and in-situ data to assess dustfall distribution in urban areas (Yan et al. 2015). Yan et al. (2015) showed that construction sites and low-rise buildings with inappropriate land-use were two main sources of dust pollution. This technique offered a low-cost and effective method for monitoring and managing dustfall in an urban environments.

In Spain, the Ministry of Agriculture and Fisheries, Food, and Environment, and the National Weather Agency have adopted the forecasts of dust surface concentration and dust optical depth released by the Barcelona Dust Forecast Center (BDFC). The BDFC is the first Regional Specialized Meteorological Centre specializing in atmospheric sand and dust forecasting, as designated by the World Meteorological Organization. It produces dust forecasts for Northern Africa, the Middle East and Europe (http://dust.aemet.es/news/dust-forecasts-available-on-the-wmo-website). Additionally, the Government of the Hong Kong Special Administrative Region, China Meteorological Authority, and Japan Meteorological Authority have adopted maps of dust pollution for monitoring and management, including the development of several tools based on satellite imagery for monitoring sand and dust weather (Sand and Dust Storm Warning Advisory and Assessment System).

Previous studies suggest that oceanic harmful algal bloom toxins can either be released into the air or accumulate in shellfish, leading to public health concerns such as asthma, ciguatera and paralytic, neurotoxic, amnesic and diarrhetic shellfish poisoning (Backer 2002, 2003, 2005; Fleming et al. 2007; Pitois et al. 2000; Randolph et al. 2008; Van Dolah 2000). Along the West Florida Shelf, blooms of *Karenia brevis* have been studied using Chla and fluorescence line height (FLH) remote sensing products derived from SeaWIFS and MODIS satellites (Hu et al. 2007; Soto Ramos et al. 2017; Stumpf et al. 2003). Satellite-derived SST, FLH, and Chla provide the tools for large-scale, early warning identification and mitigation techniques to reduce risks due to these blooms.

### *Management applications: Heat vulnerability*

To better manage heat-related health risks, information is required on the intra-urban variability of vulnerability to heat wave events (Wolf and McGregor 2013). In Brisbane, Australia, MODIS Land Surface Temperature data were used to examine the impact of temperature on childhood pneumonia (Xu et al. 2014). Mohan and Kandya (2015) investigated the effect of urbanization on the land surface temperature in India by using Terra and Aqua MODIS land surface data obtained from the Monsoon Asia Integrated Regional Study program. They called for strong and urgent heat-island mitigation measures after finding that the level of human mortality risk remained high during a prolonged extreme heat episode. This type of information has been widely used to determine heat vulnerability in different cities around the world, primarily in continental areas and mid-latitudes such as London, Toronto, Rome, Florence, Philadelphia, and Chicago (Bao et al. 2015; Morabito et al. 2015; Rinner and Hussain 2011; Wolf and McGregor 2013).

### *Management applications: VBD*

The use of satellite data for epidemiological purposes, including characterizing the environments in which vectors thrive, has improved our ability to determine disease distributions, their impacts on populations, and their changes through time (Buczak et al. 2012; Garni et al. 2014; White-Newsome et al. 2013; Young et al. 2013). Variability in environmental components, such as temperature and precipitation, has important influences on mosquito life cycles. Understanding the spatial and temporal patterns of mosquito populations is critical for control and prevention of VBD (Chuang et al. 2012). Research conducted by South Dakota State University from 2005 to 2010, used NASA's Advanced Microwave Scanning Radiometer (AMSR-E) and in-situ weather station data to successfully identify environmental metrics (e.g., air and SST, humidity, and rainfall) and better predict population dynamics of mosquitoes *Aedes vexans* and *Culex tarsalis* while improving the effectiveness of mosquito-borne disease early warning systems (Chuang et al. 2012; Méndez-Lázaro et al. 2014).

Satellite sensors provide information about a wide variety of water parameters (e.g., SST, water clarity, Chla estimates, and FLH) that can be used to understand spatiotemporal variations of vector-borne and water-borne diseases (Colwell 1996; Ritchie et al. 2003; Rodó et al. 2013). Cholera thrives in warmer waters (Colwell 2004; Epstein et al. 1993; Huq et al. 1984); therefore a combination of remote-sensing techniques and historical cholera-case data, can enable researchers to understand patterns in Cholera outbreaks. Lobitz et al. (2000) used satellite-derived SST to assess how increased water temperatures were related with increased numbers of cholera cases in coastal areas (Pascual et al. 2000; Speelman et al. 2000).

These activities have led to improvements in health management within coastal areas, especially by creating early warning systems to decrease outbreaks on coastal communities (Ho et al. 2005; Rose et al. 2001). For example, Anyamba et al. (2009) were able to produce risk-mapping models using satellite-derived SST, rainfall, and a vegetation index to accurately predict the location and timing of Rift Valley Fever activity with a 2 to 6 week period of warning for the Horn of Africa that facilitated disease-outbreak response and mitigation activities. Further, Malaria Early Warning Systems use transmission risk indicators, such as unusually elevated rainfall, to predict the timing and severity of a malaria epidemic 2 to 4 months in advance (Thomson et al. 2005; World Health Organization 2001). Early detection of the outbreaks has allowed early activation of vector control and the implementation of other effective control measures (Kiang 2009; Lee et al. 2010; Lowe et al. 2011; World Health Organization 2001).

## Fisheries and Aquaculture

There is currently a global food shortage, and therefore a need for enhanced food production (FAO 2015). A potential solution to this problem involves improving fisheries management, and the expansion of sustainable aquaculture from small-scale family practice to a highly commercial industry. To expand this renewable, rapid-growth resource, the industry needs to overcome substantial bio-physical, socio-economical, and spatiotemporal constraints (IOCCG 2009; Nath et al. 2000). The application of remote sensing and geographical information systems, in addition to traditional data and methods, may substantially improve the ability of managers to address these constraints (Meaden and Aguilar-Manjarrez 2013). Remote sensing offers a useful suite of tools that can rapidly monitor aquatic environments in terms of physical water-quality parameters (e.g., sea-surface temperature, sea-surface salinity, sea-level rise, turbidity, currents, CDOM, ice coverage, bathymetry, red tides, and oil spills), and biological processes (e.g., Chla and net primary productivity), and support facilities that influence fisheries and aquaculture planning.

### *Management applications: Fisheries*

SST observations are used to identify areas of upwelling (nutrient-rich deeper waters brought to the surface), which drive primary production and support productive fisheries (Muller-Karger et al. 2001; Rueda-Roa 2012). Fisheries managers rely on these remote-sensing products to predict fish aggregations in space and time, and to manage marine fishery resources (Santos and Miguel 2000; Lindo-Atichati et al. 2012; Habtes 2014). The search time of some US commercial fisheries is reduced by 25–50% due to the use of satellite-derived fishery aid charts (Santos and Miguel 2000). Several early studies of fisheries used the Advanced Very High Resolution Radiometer (AVHRR) and Coastal Zone Color Scanner satellite sensors to aid in monitoring tuna off of the California coast (Bakun 2006; Fiedler 1983; Laurs et al. 1984). The migration, distribution, availability, and catchability of tuna are influenced by oceanographic conditions (Laurs et al. 1984; Lindo-Atichati et al 2012). Tuna tend to aggregate along the coast near surface frontal boundaries that are associated with coastal upwelling along the central California coast. Upwelling intensity was identified via SST images from AVHRR. Fiedler (1983) studied tuna that were caught when upwelling was not constant. He found that tuna was grouped based on distance to the upwelling filaments, and the mean length and stomach volume increased with distance away from the upwelling filament. The diet of the tuna that were caught closest to the upwelling filament indicated that juvenile anchovies were in high abundance in this area as well, which helped define the limits of the spawning activity of the anchovy. Managers may use remotely sensed upwelling observations to predict the prevalence and catchability of tuna and anchovy populations in coastal regions.

The recruitment of octopi is also influenced by environmental indices such as coastal upwelling (Faure et al. 2000). Faure et al. (2000) studied the relationship between octopus recruitment and environmental indices, both of which fluctuate annually and seasonally off the Mauritanian coast. This study utilized the Meteosat sensor for SST data, and obtained wind turbulence data from the Comprehensive Ocean Atmosphere Data Set. The Mauritanian coast experiences trade winds that generate seasonal upwelling from October to June, with maximum upwelling from January to May (Faure et al. 2000). Faure et al. (2000) found that spawning takes place in and out of upwelling seasons. It was discovered that upwelling and wind-induced turbulence were linear and positive with summer recruitments, confirming that coastal upwelling primarily contributes to the summer recruitment variability of octopi. High-intensity upwelling events combined with wind turbulence create a high encounter rate between food and larvae, which favors larvae survival. Fisheries managers may use this information to identify favorable conditions for reproduction in similar fashion to commercial operations like Roffer's Ocean Fishing Forecast Service, Inc. (https://www.roffs.com/), which processes SST and other satellite-derived data to produce maps guiding fishermen to productive grounds.

### *Management applications: Aquaculture*

The top priority for sustainable aquaculture development is appropriate site selection. The process of selecting sites where natural conditions suit the cultured fish species and the impact on the surrounding environment is minimized may be substantially improved with the use of remote sensing tools and techniques (Alexandridis et al. 2008; Boyd and Schmittou 1999; IOCCG 2009; Radiarta and Saitoh 2008). Mustapha and Saitoh (2008) demonstrated the utility of remote sensing data for scallop aquaculture site selection in Japan along Funka Bay, Hokkaido by using Special Sensor Microwave Imager microwave and SeaWiFS data of ice cover and wind stress that affect the spring bloom. Others have used MODIS, SeaWiFS, and Advanced Land Observing Satellite data sets of SST, Chla, turbidity, suspended solids, and bathymetry for site selection mapping (Radiarta and Saitoh 2008; Radiarta and Saitoh 2009). Suitability modeling of the data revealed that about 83% of the bay area has optimum conditions for scallop culture (Radiarta and Saitoh 2009).

Bivalve aquaculture tended to be practiced close to the coastline where suspended PM supports phytoplankton

(Dowd 2005; Noren et al. 1999). Thomas et al. (2006) evaluated the carrying capacity of the mussel-cultured areas in the Mont St. Michel Bay, France, as well as discovering new, potential sites using daily SeaWiFS imagery. Modeling the Chla and SST data derived from the sensor and verified on the ground resulted in maps of prediction scenarios for mussel production. In New Zealand, the aquaculture of suspended mussels was practiced in the Bay of Plenty. A series of studies using AVHRR images, and SeaWiFS images for SST and Chl-a, respectively, identified the most productive regions based on bathymetry, currents, and upwelling conditions (Longdill et al. 2007; Longdill et al. 2008a, b, c). After multiplying the normalized monthly climatological anomalies of SST and Chla together, all layers were converted to 200 m$^2$ spatial resolution excluding the locations more than 30 km from the coast or deeper than 100 m. The output models were subjected to multi-criteria evaluation techniques to achieve the best sustainable management plan for the mussel culture (Aguilar-Manjarrez 1996; Arnold et al. 2000; Carrick and Ostendorf 2007; Vincenzi et al. 2006). The results of Longdill et al. (2008c) showed that only 18% of the bay area was classified as most suitable for mussel aquaculture, and 46% was classified as unsuitable (Fig. 4).

Coastal aquaculture has increased rapidly in recent years all over the world, as has interest in monitoring such practices. In 2007, South Africa launched a satellite designed to track aquaculture production and to predict fish yield. The 15 m spatial resolution, hyperspectral satellite named Multi-sensor Microsatellite Imager has 200 spectral channels, and a revisit time of 10 days (Steyn 2010; Quansah et al. 2007). Delineating aquaculture coasts is difficult when using traditional automated mapping methods due to the spectral similarities between aquaculture regions and ocean. However, a process called object-based region growing integrated with edge detection (OBRGIE) was achieved to delineate aquaculture coastlines by Zhang et al. (2013). The OBRGIE method was found to be much more effective than the spectral attribute in separating land and sea in aquaculture coasts of the Bohai Sea in Northern China and Zhujiangkou Estuary in Southern China using Landsat and SPOT-5 multispectral images, respectively.

## Challenges

Many challenges in the interpretation of satellite data for coastal-management applications remain. For example, cloud cover interferes with visible light, and therefore hampers the use of imagery collected in the visible and infrared range of the electromagnetic spectrum. This issue may be avoided, depending on the research application, by using imagery collected in the microwave range of the

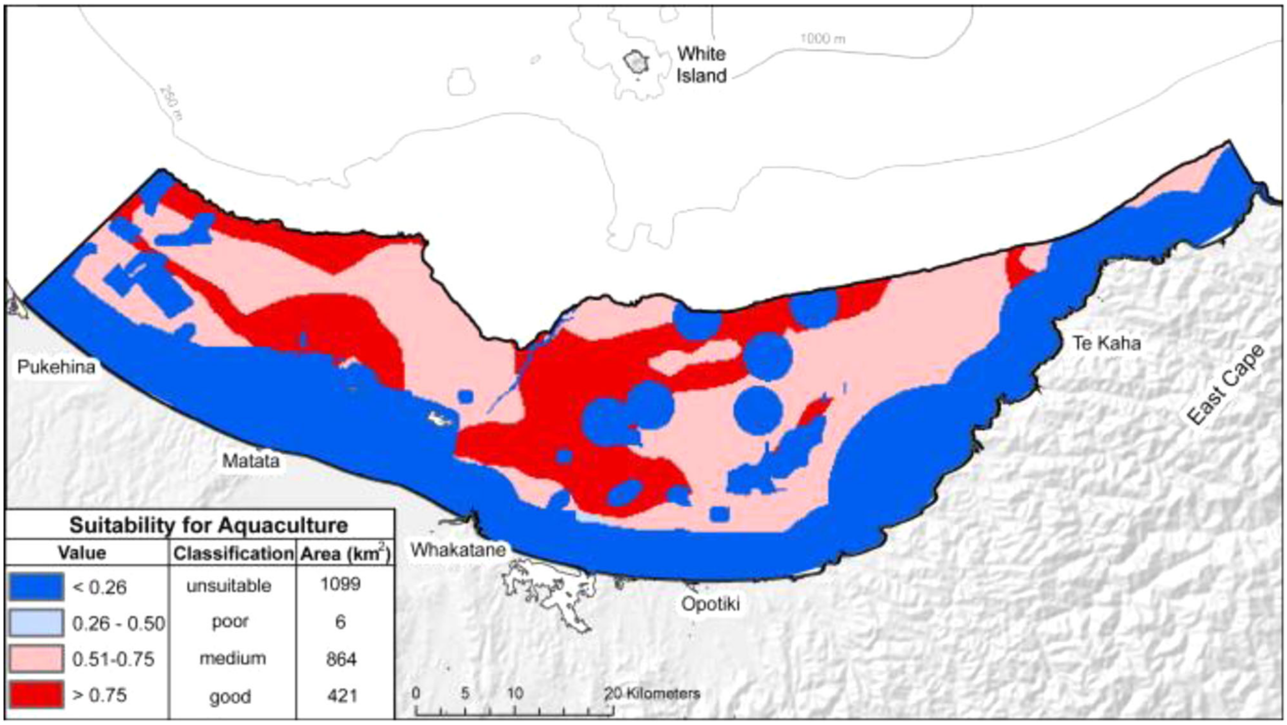


**Fig. 4** Suitability map for offshore bivalve aquaculture in the Bay of Plenty, New Zealand (Longdill et al. 2008c). Suitability determination incorporated SST and Chl-a estimates from AVHRR and SeaWIFS sensors

electromagnetic spectrum because it is not affected by cloud cover (Dabrowska-Zielinska et al. 2009), or by using imagery with high temporal-resolution (i.e., frequent repeat times), which may provide more opportunities for acquiring cloudless imagery. Also, variability in the concentration and type of light-absorbing aerosols is quite high in the coastal zone, a problem that can easily confound existing approaches to atmospheric correction. Therefore, accurate atmospheric correction is vital to the generation of usable remote sensing products.

In addition to atmospheric corrections, reflectance from the seafloor in coastal shallow areas has to also be removed from remotely sensed data when studying properties of the water column itself. Algorithms designed to estimate Chla concentration from satellite data, for example, rely on the use of spectral bands in the visible portion of the spectrum where light readily penetrates the water and reflects off the bottom (Bukata 2005). The removal of bottom contribution to satellite images, specifically for optically clear waters, continues to be a difficult task, although important advances have been made (Barnes et al. 2013b). One solution is to simply mask or eliminate areas shallower than a specific depth using bathymetry data.

When mapping wetlands and other coastal habitats, tides and other water level variations must be accounted for, especially when comparing images acquired at different times of day or year (McCarthy and Halls 2014). Maps of submerged and intertidal vegetation may be especially affected by variations in water level, as well as by water column components (i.e., suspended sediments, phytoplankton, and dissolved organic matter). Ideally, time series images will be selected with acquisition times that coincide with identical water levels. Accurate water levels are necessary to account for these variations. More broadly, we recommend that accuracy assessments of any satellite-derived product be gathered either ad hoc by data users, or from data providers upon request.

Many coastal management studies have utilized the freely available MODIS, SeaWiFS, AVHRR, Landsat imagery, which includes several decades of continuous data coverage, and offers a medium-spatial to high-spatial resolution that affords near-global coverage of land areas every year. Higher spatial-resolution commercial imagery, such as that from IKONOS, QuickBird, and WorldView-2, has been used for local/regional coastal resource case studies, but it may be cost-prohibitive to expand the use of such imagery to larger study areas for now (Alexandridis et al. 2008; Belluco et al. 2006; Chust et al. 2008; IOCCG 2009; Ghioca-Robrecht et al. 2008; McCarthy and Halls 2014; McCarthy et al. 2015). Nevertheless, MacKay et al. (2009) noted that, for wetland mapping, high-spatial resolution imagery (i.e., 1–4 m resolution) is likely more useful than high-spectral and medium-spatial (i.e., 10–30 m) resolution imagery due to the small, heterogeneous spatial structure of wetlands worldwide.

For many applications of remote sensing data to management goals, additional interdisciplinary research between coastal managers and environmental scientists is needed. Web-based portals are emerging as powerful platforms for managers, scientists, and the public to obtain historical and near-real time satellite data. Despite discussions on shared regional governance of living marine resources (Chakalall et al. 2007; Fanning et al. 2009), limited integrated environmental data analysis and visualization tools exist for the US territories and international community. Local management initiatives for the sectors discussed here, among others, could benefit from readably accessible online portals, such as NOAA's Coral Reef Watch website (https://coralreefwatch.noaa.gov/satellite/index.php; Cho 2005; Ortiz-Lozano et al. 2007).

## Conclusions

As the global population continues to rise and concentrate along coasts, current approaches to managing coastal resources require updating. Successful management requires local interventions coordinated across ecologically appropriate spatial scales, and is best guided by frequent and synoptic sampling and monitoring (Sale et al. 2014). This work reviews recent, demonstrated applications of remote sensing technology for management of coral reefs, wetlands, water quality, fisheries and aquaculture, and public health. Challenges to the use of remote sensing data for these purposes have been addressed here, and must be considered before implementing these approaches for coastal-resource management. Space-based remote sensing tools enhance the ability of coastal-resource managers to keep pace with increasing population-pressure on coastal resources, and improve climate change adaptation strategies. We encourage coastal managers to take advantage of this technology to supplement traditional management approaches toward the goal of preserving both human and ecosystem health.

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### Compliance with Ethical Standards

**Conflict of Interest** The authors declare that they have no competing interests.

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