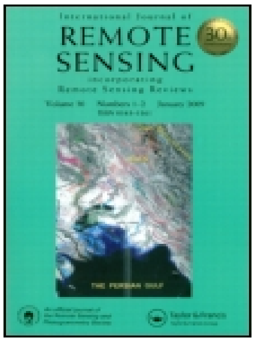

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Barriers to adopting satellite remote sensing for water quality management

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Sustainable practices require a long-term commitment to creating solutions to environmental, social, and economic issues. The most direct way to ensure that management practices achieve sustainability is to monitor the environment. Remote sensing technology has the potential to accelerate the engagement of communities and managers in the implementation and performance of best management practices. Over the last few decades, satellite technology has allowed measurements on a global scale over long time periods, and is now proving useful in coastal waters, estuaries, lakes, and reservoirs, which are relevant to water quality managers. Comprehensive water quality climate data records have the potential to provide rapid water quality assessments, thus providing new and enhanced decision analysis methodologies and improved temporal/spatial diagnostics. To best realize the full application potential of these emerging technologies an open and effective dialogue is needed between scientists, policy makers, environmental managers, and stakeholders at the federal, state, and local levels. Results from an internal US Environmental Protection Agency qualitative survey were used to determine perceptions regarding the use of satellite remote sensing for monitoring water quality. The goal of the survey was to begin understanding why management decisions do not typically rely on satellite-derived water quality products.

1. Introduction

The world population was estimated at over seven thousand million (7×10^9) people as of summer 2012. Between 30% and 70% of the world population lives within 100 km of a coastline (UNEP 2007; Wilson and Fischetti 2010). Sustainable water management practices take into account the environment, human health and well-being, and economic considerations. Coastal area recreation benefits human well-being and quality of life due to increased contact with the natural environment (Cox, Johnstone, and Robinson 2006). Similarly, Wheeler et al. (2012) found that at all socioeconomic levels human health

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*Corresponding author. Email: schaeffer.blake@epa.gov increases as people live closer to the coast. Water quality also has an impact on economies, such as changes in property valuation and visitor decisions, which ultimately impact tax revenues (Dodds et al. 2009). Measures of water quality are traditionally tied to water clarity measures, readily derived from satellite remote sensing, since it is the most obvious metric to the general public. For example, eutrophication in lakes has historically been identified as a cause for appraisal declines in residential property, especially in proximity to the degraded waterbody. In the northeastern USA, a 1.0 m decline in lake water clarity translated to a 1–6% decline in property value (Gibbs et al. 2002). Conversely, improvements in water clarity can result in property price increases (Michael, Boyle, and Bouchard 1996). Additionally, visibility of coastal waters has provided a premium for homes with waterfront views, between 10 and 200% higher than those homes further away from the waterfront (Major and Lusht 2004). Water quality has also been identified by the European Union as an important economic driver. In Scotland, improvements in water quality may have resulted in a 1.3% increase in visitors along the coast contributing almost an additional two million (US dollars) per year to the local economy (Hanley, Bell, and Alvarez-Farizo 2003).

Water quality monitoring by management agencies is traditionally labour intensive and cost prohibitive, limiting sample collection over temporal and spatial scales (Bierman et al. 2011). Even for agencies with ambitious sampling plans, water collection stations may represent a small percentage of waterbody spatial extent. When sampled, measurements are often localized and may not represent neighbouring waters. Samples taken on any given day may not adequately represent the water quality of that location over a week, month, or season. This leads to coarse sampling that is insufficient for capturing fluctuations in water quality. The dynamic nature of coastal systems necessitates finer-scale monitoring, both temporally and spatially. Such initiatives are costly using traditional methods, thus requiring agencies charged with water quality monitoring to utilize new tools to achieve monitoring goals. Transitioning to new tools has occurred previously, such as in the case of *in situ* chlorophyll fluorometers, turbidity meters, and photosynthetically active radiation (PAR) sensors supplementing discrete samples of extracted chlorophyll-*a*, total suspended solids, and Secchi depth (Glasgow et al. 2004). Similarly, the use of remote-sensing satellite data to estimate water quality measures provides expanded sampling coverage and cost savings. As operating budgets continue to shrink and prioritization of sampling stations occurs, satellite datasets offer managers a way to gain water quality information at unprecedented temporal and spatial scales (Bierman et al. 2011).

Satellite remote sensing enables policy makers and environmental managers to assess the sustainability of watershed ecosystems, and the services they provide, under current and future land-use practices. The most direct way to ensure that management practices are achieving sustainability is to monitor the environment on a synoptic scale. Satellite technology allows for the development of water quality monitoring at the local scale with national coverage. The goal of this project was to begin understanding why management decisions do not typically rely on satellite-derived water quality products and to provide information to adequately address concerns.

2. Remote sensing and potential water quality management applications

Eutrophication assessment frameworks such as the Australian National Water Quality Management Strategy, Oslo Paris (OSPAR) Commission Common Procedure, Water Framework Directive (WFD) of the European Union, Marine Strategy Framework Directive (MSFD) from the European Commission, French Research Institute for Exploration of the

Sea (IFREMER) method, Helsinki Commission (HELCOM) Eutrophication Assessment Tool (HEAT), and in the USA the National Coastal Assessment and National Aquatic Resource Assessment use various approaches for assessing water quality and status of coastal and inland waters (Park, Ruddick, and Lacroix 2010; Devlin, Bricker, and Painting 2011; Ferreira et al. 2011; Dekker and Hestir 2012). These assessment frameworks are typically based on defining a baseline, and then assessing current conditions to assign a level of eutrophication or overall ecological status to coastal waters. In addition, all navigable waterbodies in the USA are protected by the Clean Water Act (CWA 1988). The objective of the CWA is to 'restore and maintain the chemical, physical, and biological integrity of the Nation's waters'. This federal mandate authorizes states, tribes, and US territories, with guidance and oversight from the US Environmental Protection Agency (EPA), to develop and implement water quality standards to protect the resources of the Nation's waters. Water quality standards include designated uses, defined as the services that a waterbody provides such as drinking water, aquatic life, harvestable species, and recreation. These standards under the CWA are applicable within state waters, defined as <3 nautical miles from shore. Therefore, a majority of water quality management decisions address nearshore coastal waters, estuaries, lakes, reservoirs, rivers, and streams where applicable water quality regulation could be implemented.

Few management decisions rely on satellite-derived water quality products. Instead, current methods for measuring water quality focus on periodic (boat-based) or continuous (ship-based or buoy-based) monitoring models. The periodic approach typically incorporates fixed sampling locations that correspond to locations of geographic interest or incorporate a statistical sampling frame (e.g. probabilistic), and are sampled based on an established time-line to coincide with a specific sampling interval, seasonal events, regulatory mandate, or event-driven phenomenon (Overton, White, and Stevens 1990; Stevens 1994). In contrast, ship-based models typically incorporate nearly continuous (spatial) sampling along transects that are collected periodically (sampling cruise) or nearly continuous collections (Ensign and Paerl 2006). More recently, buoy monitoring stations have been developed incorporating the latest field sensor miniaturization and data transmission technologies to provide nearly continuous (temporal) monitoring data at fixed individual sample locations. Finally, approaches commonly used for small inland lakes by community-based sampling programmes include the Mid-lake, Deep-point, or Dock-end approaches (Brenzonik, Menken, and Bauer 2005, US EPA 2011).

Traditional water quality measures typically include measures of chlorophyll-*a*, suspended material, light attenuation, and coloured dissolved organic matter (CDOM), all of which are currently derived from satellite ocean colour technology. For a review of measurable variables from satellite remote sensing see Muller-Karger (1992). Chlorophyll-*a* is used as a proxy for phytoplankton biomass and can be an indicator of increased nutrients (Devlin, Bricker, and Painting 2011; Ferreira et al. 2011; Schaeffer et al. 2012) or a direct measure of potential harmful algal bloom development (Stumpf et al. 2003). Suspended material includes phytoplankton and sediment particles, which is important for monitoring wind-driven resuspension events, is a predictive factor for pathogens such as *Escherichia coli* (Nevers and Whitman 2005), and a valuable tracer of anthropogenic disturbance to land. Light attenuation provides a measure of available light throughout the water column, which is important for the growth and maintenance of suspended (phytoplankton) and benthic (seagrass) plant life (Gallegos 2001). CDOM serves as a nutrient source, sunscreen for plants and animals, and a vector for heavy metals in water. Detection from space provides a measure of river plume extent and transfer of organic carbon (Tehrani et al. 2013), both critical to management of coastal aquatic resources.

Water quality parameters are derived by satellite through direct solar radiation entering the water column and absorbing or scattering, depending on the types and concentrations of constituents within the water column. The radiation is then reflected back to the atmosphere as water-leaving radiance. The ratio of the radiance reflected out (W m^{-2}) to the direct solar radiation incident on the sea surface is termed the reflectance. When the reflectance is passively recorded by a sensor it is referred to as remote-sensing reflectance. Remote-sensing reflectance represents the 'ocean colour signature' of the water, which integrates the spectral absorption and backscattering properties of all the materials present in the water column (Coble et al. 2004). Colour is determined by the mixture of pigments in phytoplankton, the absorption of light by CDOM, and the concentration of minerals or inorganic matter present in the water column (IOCCG 2000). Managers and policy makers without technical expertise typically lack the knowledge to understand these physical descriptions. Illustration of the ocean colour physics is sometimes better understood with an analogy to the human eye. For example, ocean colour derivation of products is similar to a person differentiating green water dominated by algae, from brown water dominated by suspended sediment, and from tea-coloured water dominated by CDOM. By a similar method, the satellite identifies the change in colour spectrally and quantifies the concentration via validated algorithms.

Coastal and inland waters contain a wide variety of optically active constituents that affect the underwater light regime and water quality. Particulate and dissolved material such as phytoplankton, detritus, suspended sediments, pollution, and CDOM varies over orders of magnitude in concentration. In addition, processes that affect their distribution, such as upwelling, river discharge, frontal formation, waves, wind resuspension, and biological growth vary over shorter space and time scales than in the relatively more homogeneous open ocean. All these factors combine to create an optically complex system. Because the absorption properties of the water components exhibit broad, overlapping spectral features, typical multispectral ocean colour remote-sensing imagers, such as the Moderate Resolution Imaging Spectroradiometer (MODIS), with just a few (7) spectral bands of information at visible wavelengths and coarse spatial resolution (1.0 km), are typically limited in their ability to adequately separate and resolve them. Water quality algorithms for these sensors typically rely on band ratio approaches using just a few bands (O'Reilly et al. 1998; Morel and Gentili 2009), but new and novel multivariate approaches are needed (IOCCG 2000). In addition, the highly reflective surface of land compared with that of water causes error flagging of remotely sensed water quality data at the coastline. If cloud masking is applied during image processing, extremely turbid coastal waters can often be flagged incorrectly as clouds (Shi and Wang 2007), unless the default processing threshold for cloud albedo (which uses the 869 nm channel) is increased. Straylight contamination and bottom reflectance typically confound the derivation of remote-sensing products where environmental management needs are greatest along the coastline (Schaeffer et al. 2012). Methods developed with MODIS, the Medium Resolution Imaging Spectrometer (MERIS), and Sea-viewing Wide Field-of-view Sensor (SeaWiFS) have demonstrated some success for deriving water quality products in coastal and inland waters (Miller and McKee 2004; Gons, Auer, and Effler 2008; Werdell et al. 2009; Witter et al. 2009). In addition, the Hyperspectral Imager for the Coastal Ocean (HICO) may have potential to resolve water quality measures with greater spatial resolution than existing ocean colour sensors. This proof-of-concept sensor is the first test platform of an ocean colour imager specifically designed to measure water quality parameters within coastal waters (Corson and Davis 2011).

3. Qualitative survey

An initial internal EPA qualitative survey of selected individuals was conducted to determine what perceptions existed regarding satellite remote sensing and water quality applications. The goal of the survey was to begin understanding why management decisions do not typically rely on satellite-derived water quality products. This survey was provided to 15 individuals with a range of expertise and knowledge, some very familiar with satellite technology and others having no background. Participants were selectively sampled due to their specific job responsibilities, which included integrating scientific research into policy and management decisions. An interview guide ensured that each discussion followed a similar line of inquiry (Patton 2002). The questions were structured to allow the participants to create their own responses and not feel constrained by the perspective of the interviewer (Creswell 2005). Probing questions were used to deepen the responses of participants and add more detailed information (Patton 2002). Interviews were advantageous because they allowed the participant to provide a detailed perspective, and for the interviewer to guide the focus of the study. The negative aspect of interviews was that the perspectives gained were filtered through the views of only a few interviewees (Creswell 2005). After data collection, a preliminary coding scheme was developed based upon the research questions. Theoretical perspectives as well as the interviewer's values impacted what codes were used (Bogdan and Biklen 2007). Coding analysis was a way to reduce the amount of data in order to look for themes. Initial codes were words, phrases, or ideas that stood out after an initial review of the data. All codes that were relevant to the research questions were noted. Similar codes were grouped together to develop larger themes or clusters of meaning within the data (Moustakas 1994). Four main themes were identified in the interviews: cost, accuracy of data products in the particular waterbody of interest, satellite mission continuity, and obtaining management approval for including satellite data into their work (Table 1).

3.1. Cost

There was an impression that all satellite imagery could only be obtained with a financial commitment. It was not widely known that data from SeaWiFS, MODIS, MERIS, VIIRS, and, in the future, the Ocean and Land Colour Instrument (OCLI) on Sentinel-3 and Pre-aerosol, Clouds and Ocean Ecosystem (PACE) were available free of charge. For example, one interviewee commented: 'I assume it would cost some money to access the [satellite] data and if there is no money available I don't know how that could be overcome'. It was not clear how the misconception that all satellite-derived water quality products must be purchased developed. The perception of cost may stem from experiences in the past, as one interviewee commented: 'In the past it wasn't easy to get [satellite] information, it was expensive and if you wanted a certain area it was very expensive and you had to partner . . . to get the images you wanted'. The Landsat programme previously charged for satellite imagery (Turner et al. 2003) and there are charges for commercial imagery such as WorldView and GeoEye. Many interviewees also expressed a desire to reduce costs for traditional field sampling and use satellite imagery if possible. A common interest in leveraging included, '[satellites] measure . . . six out of the 50 parameters they [water quality managers] need and you can save them on those six and use that money toward the other [parameters]'. Cost was previously indicated as a constraint not only in relation to availability of data, but also in regard to personnel and resources required to process the data (Specter and Gayle 1990). Typical up-front costs include hardware and required expertise to enable adequate data processing and interpretation (Turner et al. 2003). However, after

Table 1. General question from the interview and summary of responses, including keywords.

Questions	Response summaries
Tell me what you know about satellite technology.	They can be used for: • Chlorophyll measurement • Nutrient concentration • global positioning system (GPS) • geographical information system (GIS) • Remote sensing • Imagery • Otherwise limited knowledge
Did you know satellite technology could be used for water quality measurements?	Yes, but approximately half of the respondents had a limited knowledge of the use of satellite technology and its use to measure water quality.
What do you know about satellite technology and water quality applications?	They can be used for: • Temperature • Chlorophyll • Nutrients • An analysis of algal blooms
Have you, or anyone you know, used data from satellites? a) How have you used these data? b) If you have never used satellite date, why not?	Approximately half of the respondents knew someone who had used satellite data but most had not used it themselves. a) Monitor algal blooms with JPEG images; monitor Gulf Coast oil spill; thematic maps b) Lack of expertise; lack of confidence in the product; lack of funding
What justification do you need to use satellite data?	• Reliability • Validity • Ground truthing • Standardization of measurements • Cost effectiveness
What problems could be addressed using these data?	• Chlorophyll • Sea surface temperature and sea level rise • Turbidity • Sedimentation • Nutrients • Monitoring algal bloom
What are the roadblocks to using these data?	Participant responses varied widely. • Reliability • Cloudy days • Spatial resolution • Cost • Data processing • Availability of the technology • Divide between technical staff and management • Fully trained staff • Lack of understanding about the technology • Data storage
If training was made available, would you be willing to use satellite data? What type of training would you want?	Yes. Training would need to include both a general overview of the uses of satellite data and hands-on training interpreting and applying data. There was also concern that training should address the buy-in of both managers and technical staff.
If we are successful in demonstrating the validity and application of the satellite date, would you use them? Why or why not?	Yes, but that response is dependent on cost and the relevance of the data to the particular problems that are being researched.

the initial expense a potential return on investment is the ability to monitor spatial and temporal scales at orders of magnitude greater than traditional *in situ* monitoring can readily achieve.

3.2. Product accuracy

Almost unanimously, interviewees wanted assurance that the satellite product could be validated and include reported accuracy or error estimates for their particular waterbodies, regardless of the location of previous validation. For example, managers focused on Chesapeake Bay want to see products validated specifically for Chesapeake Bay and would not likely be satisfied with products that are validated for other estuaries along the East Coast. Interviewees agreed that if a product was proved to provide an accurate measure in their particular waterbody of interest, they would be open to using those products for their monitoring, research, and assessments. While it was not discussed what an accurate measure would constitute, it seemed generally acceptable that if the results were published in peer-reviewed journals, with clear definitions of the errors and the validation regression was significant ($p < 0.05$), it would be considered for use. Many interviewees provided comments along the lines of: '[environmental managers] would want to know how reliable the data were and what the error around it is and how frequently the data were updated and maybe what the interferences were'. Product accuracy will vary depending on derived product region of interest, and time of the year. Accuracy will also vary due to concentration of the substance, availability of appropriate wavebands, atmospheric corrections, and the accuracy of the *in situ* data set. Typical accuracy targets for most ocean colour products were better than ±30% (IOCCG 2000). There was a wide perception that validating satellite data meant that traditional *in situ* samples represented 'truth'. There was less concern regarding the error with *in situ* measurements, even though accuracy and reliability issues also exist for these accepted standard methods (Trees, Kennicut, and Brooks 1985). Water quality managers must remember that a satellite-derived product, such as chlorophyll-*a*, represents a large spatial area (30 m for Landsat to 1.0 km for MODIS), whereas the variability of chlorophyll-*a in situ* may be orders of magnitude within a satellite single pixel. Yet, a single *in situ* sample may often be deemed representative for a body of water. The additional value of satellite remote sensing is not always absolute accuracy of individual retrievals, but synoptic and frequent coverage of numerous waterbodies. Even with uncertainties in accuracy estimates, parameter concentration change could be detected if the product was derived with a consistent methodology (Stumpf et al. 2003; Hu et al. 2005).

3.3. Data continuity

Mission continuity seemed relevant to the level of effort water quality managers may invest when considering the inclusion of satellite technology. One comment summarized the concern: 'Of course there is always the issue as to whether or not satellites go off-line in the future . . . If satellites would go off-line . . . and there is no funding to put satellites in orbit to do this work than that would definitely cause some concern'. This concern was certainly valid with the recent conclusion of SeaWiFS, Landsat-5, and MERIS missions. Multi-mission ocean colour satellites are necessary to provide future climate data recording to continue the monitoring and assessment process. Continuity in derived products will also be important for complete climate data records and the ability to continue monitoring into future transitioning between missions. The National Aeronautics and Space

Administration (NASA) Ocean Biology Processing Group made significant progress on standardized methods for generating Level 1 and 2 products for successive missions (Franz et al. 2005; Hooker, Mcclain, and Mannino 2007). Without a continued strong and visible commitment from these groups and agencies, long-term investment by water quality managers will be a challenge.

3.4. *Programmatic support*

Buy-in and support from organizational management was important. Using satellite technology for water quality monitoring and assessment would require new training, new software applications, and at least a basic understanding of the fundamentals behind remote-sensing technology. For example, one interviewee stated: '. . . what is critically important if there is some type of top down support or training for this technology . . . people here, just like people everywhere, are so busy with doing their day-to-day work that it is hard for them to . . . focus on something new'. A second interviewee commented along the same lines: 'No matter how great the science is, if there is no [organizational management] commitment to use it [satellite technology] the interest is going to wane'. Specter and Gayle found similar concerns, which included the need for experienced personnel and education of environmental managers or stakeholders (1990).

4. Conclusion

It is important to develop solutions to clarify perceptions of environmental managers. Although this should be straightforward, it is not necessarily simple or readily achieved. The difficulty in developing these solutions was illustrated by the fact that similar issues, identified 22 years ago by Specter and Gayle (1990), still exist today. The solution begins with initiating an open and effective discussion and forum between scientists, stakeholders, policy makers, and environmental managers. While this solution is certainly not new or novel, it is important and fundamental when bridging the gap in understanding a new technology such as satellite remote sensing. We recommend that researchers who work in the field of optics and remote sensing continue to take additional steps beyond publishing manuscripts in peer-reviewed journals and work with federal, state, and local environmental managers on using appropriate tools that are available to address important monitoring needs. Satellite technologies have the potential to provide spatial and temporal coverage that will not otherwise be possible through traditional field sampling. To clarify, satellite technology alone will not be the answer to all of the problems that need to be addressed by policy makers and environmental managers. However, it offers a significant step forward in tackling some basic and fundamental issues regarding monitoring, and can be used in conjunction with traditional measurement programmes to assess the sustainability of water resources and watersheds, under current and future land practices. Optimally, future networks will be implemented that incorporate both *in situ* and remote-sensing assets to provide comprehensive data solutions to address sustainability issues.

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