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Remote sensing and GIS applications for estuarine ecosystem analysis: an overview

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This article provides an overview on the status of remote sensing and Geographical Information System (GIS) applications in developing landscape-level environmental indicators for estuarine ecosystem assessment. These broad-scape indicators are related to near-shore water quality, submergent aquatic vegetation, coastal wetlands, as well as watershed landscape structure and pattern. Slightly different from other general reviews, this paper focuses more on the contributions included in this Special Issue that highlight the remote sensing and GIS research conducted by scientists from the US EPS EaGLe (Estuarine and Great Lakes) Program. Following on from the content of this Special Issue, some future research priorities are identified which may be particularly useful to meet the needs of estuarine researchers and resource managers. Finally, the research needs and major challenges for integrated assessment of an estuarine ecosystem by using remote sensing and GIS are discussed.

1. Introduction

The ecological significance of estuaries has been discussed elsewhere (e.g. Hobbie 2000). The needs for broad-scale environmental indicators in the assessment of an estuarine ecosystem were elaborated in several other articles (e.g. Klemas 2001, Niemi *et al*. 2004, Levinson 2005).

The primary goal of this article is to provide an overview of the most recent developments of remote sensing and Geographical Information System (GIS) applications for estuarine ecosystem analysis. Slightly different from several other general reviews (e.g. Cracknell 1999, Klemas 2001, Liu *et al*. 2003), the focus here is more on the contributions of this Special Issue that feature the remote sensing and GIS research conducted by scientists from the EaGLe (Estuarine and Great Lakes) Program. Since 2000, the US Environmental Protection Agency (EPA) has established five EaGLe research centres targeting a range of diverse estuarine and coastal ecosystems in the Atlantic Coast, Pacific Coast, Gulf of Mexico and Great Lakes in the USA. The goal of the EaGLe Program was to develop nested suites of environmental indicators that can quantify the integrated condition of coastal ecosystems and identify their primary stressors across a range of scales (Levinson 2005). The remote sensing component was established within the EaGLe Program to help develop landscape-level environmental indicators. Over the past four years, remote sensing investigators have teamed with biologists and ecologists in many co-ordinated projects targeting some of the nation's most valuable and stressed estuaries. The Special Issue reports some of the most exciting developments of these research efforts.

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This article reviews the status of remote sensing and GIS applications in developing landscape-level environmental indicators for estuarine ecosystems and identifies a number of future research directions that may be particularly useful to meet the needs of estuarine researchers and resource managers. The specific objectives are:

(a) to describe the status of remote sensing and GIS applications for developing broad-scale environmental indicators that are related to water quality, submergent aquatic vegetation, wetlands and watershed landscape structure and pattern;
(b) to review the contribution of this Special Issue to these research areas;
(c) following on from the content of this issue, to define a number of areas in which future research is needed; and
(d) to discuss the research needs and major challenges for an integrated estuarine ecosystem assessment by using remote sensing and GIS.

2. Remote sensing of estuarine water quality

Remote estimates of coastal water quality indicators, such as chlorophyll-*a*, turbidity, dissolved organic matter (DOM), total nitrogen, temperature and salinity have been under development for almost two decades. They are based on either a radiative transfer algorithm or a statistical correlation model.

Airborne remote sensing may be the most useful for small, shallow, or optically complex coastal waters where cloud-free data with high spatial resolution are needed. The existing space-borne colour scanners have been designed primarily for open oceans and their coarse spatial resolutions limit the ability to monitor near-shore coastal waters accurately. Many researchers have been successful in remote sensing of near-shore coastal and estuarine waters by using satellite data from terrestrial remote sensors, such as Multi-spectral Scanner (MSS), Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), SPOT HRV, IKONOS and Quickbird (e.g. Mumby and Edwards 2002, Zhu *et al.* 2002, Erkkila and Kalliola 2004, Hellweger *et al.* 2004). In this Special Issue, Han and Jordan (2005) report a continued effort in developing practical algorithms to estimate chlorophyll-*a* concentration from ETM+ data for Pensacola Bay on the Gulf of Mexico. Their method was built upon the regression analysis using *in situ* chlorophyll-*a* measurements as the dependent variable and raw bands, various band ratios and logarithmically transformed band ratios as the independent variables. They found that the ratio of Band1/Band3 was the most effective in estimating chlorophyll-*a*. Their study also identified higher chlorophyll-*a* concentrations along the coastline, indicating the higher abundance of benthic algae, and near the outlets of several rivers suggesting higher abundance of phytoplankton.

Compared with multi-spectral radiometers, hyperspectral sensors offer extremely high spectral resolution that can help discriminate complex bio-optical properties of coastal waters (Richardson 1996). Derivative spectroscopy has been quite promising for use with hyperspectral data (Demetriades-Shah *et al.* 1990, Goodin *et al.* 1993, Tsai and Philpot 1998). In this Special Issue, Han further demonstrates the effectiveness of derivative analysis in estimating chlorophyll-*a* concentration from coastal waters (Han 2005). He used a portable field spectroradiometer to measure the upwelling radiance of water from 16 sampling stations in Pensacola Bay. It was found that the first derivative spectra were relatively free from wind-derived wave effects and that the spectral regions 630–645 nm, 660–670 nm, 680–687 nm and

700–735 nm are potential regions where accurate chlorophyll concentration can be estimated by using the derivatives. The findings may be helpful in designing future hyperspectral sensors for coastal and estuarine waters.

There are several areas where further research is needed in order to improve the success of remote sensing in estimating estuarine and coastal water quality. First, the current ocean colour scanners are basically designed for deep offshore waters. They are of little use for optically complex near-shore waters. Further research is needed to help design future ocean colour radiometers appropriate for shallow coastal waters. Secondly, hyperspectral radiometers are considered to be the future sensors for coastal water quality monitoring. In order to exploit their full potential, further research is needed to develop methods that can be used to interpret the vast amounts of information from spectrally continuous data. Lastly, a significant area for continuing research is the fundamental understanding of the functional linkage between water constituents and remote reflectance.

3. Submergent aquatic vegetation mapping

Because of its significant ecological role and sensitivity to water quality parameters, submergent aquatic vegetation (SAV) has been used as an important biological indicator to assess the water quality and, thus, the health of large rivers and estuaries (Dennison *et al.* 1993, Stevenson *et al.* 1993, Short and Burdick 1996, Livingston *et al.* 1998, Nieder *et al.* 2004). There are two major empirical approaches that can be used for mapping the spatial distribution of SAV. The first method is basically an image interpretation approach, suitable for aerial photography or high-resolution satellite imagery. SAV mapping can be completed through automated image classification (Ackleson and Klemas 1987). In this Special Issue, Wolter *et al.* (2005) describe an effort to map SAV by using unsupervised classification from orthorectified Quickbird satellite data. Their three study sites were across the Great Lakes in the USA. To support automated classification, they collected field data across different transects, recording water depth, Secchi depth, substrate type and SAV species at each location. They compared the SAV classification results by using single- vs. multi-date scenes, and found that the later showed less confusion between deep water and SAV. They also found that the spectral variability caused by the sub-surface sandbar structure was the major source of classification errors for both single- and multi-date classifications.

Additional research effort is needed to improve the accuracy of SAV mapping. Wolter *et al.* (2005) suggest that detailed bathymetric data could help improve the performance of SAV classification. Further investigation is needed to explore the benefits of incorporating bathymetric and other auxiliary data for SAV mapping. Another significant area for continuing research is the fundamental understanding of the relationship between the volumetric reflectance, SAV canopy density, water depth and bottom reflectance parameters. This will help develop realistic volumetric reflectance models, thus increasing the likelihood of accurate SAV mapping.

4. Coastal wetland mapping

Remote sensing has been used in wetland mapping for several decades. Early inventories were largely based on aerial photography through an image interpretation method. The automated classification method has been used primarily for data obtained from satellite sensors such as Landsat MSS, TM, ETM+ or SPOT HRV. Under unfavourable weather conditions, microwave or radar products should be used that can help identify broad wetland classes (e.g. Rao *et al*. 1999, Kushwaha *et al*. 2000).

For some applications such as investigating wetland degradation by the intrusion of certain less valuable species or characterizing wetland structure, plant species will need to be differentiated. For this task, remote sensing with a broad-band sensor may be problematic due to its inability to provide sufficient spectral details. Several researches demonstrated that hyperspectral remote sensing has been quite promising in distinguishing coastal wetland plant species (Zhang *et al*. 1997, Li *et al*. 2005, Rosso *et al*. 2005).

There are three papers in this Special Issue that concern the development of methods and technologies for coastal marsh mapping by using hyper-spectral imagery. Rosso *et al.* (2005) explore the adequacy of using hyper-spectral imagery to determine the structure of wetlands, with a special emphasis on the presence of *Spartina* species and hybrids. The study area is at the southern extreme of the San Francisco Bay, California, USA. To support this effort, they assessed the spectral separability of several major pant species at a fully and healthy canopy by using a field spectrometer. Their actual mapping was based on Airborne Visible and Infrared Imaging Spectrometer (AVIRIS) data. Spectral mixture analysis (SMA) and multiple endmember spectral mixture analysis (MESMA) were applied on the AVIRIS data and the rms. error was computed to measure model adequacy. They found that both SMA and MESMA are suitable for mapping the major components of the marsh, although MESMA appears to be more appropriate because it can incorporate more than one endmember per class.

Li *et al.* (2005) further investigated MESMA application to AVIRIS imagery for mapping coastal salt marsh at San Pablo Bay, the northern extension of the San Francisco Bay, California, USA. They selected the best endmember model by using the spectral angle together with physically meaningful fraction and the rms. error between modelled and original pixel spectra. The resultant fraction image was used to investigate the spatial distribution of three dominant species, namely *Salicornia*, *Grindelia* and *Spartina*. They compared the mapping result with field Global Positioning System (GPS) polygons and found that the classification of *Spartina* and *Salicornia* was reasonably accurate. The classification of *Grindelia* was not that accurate due to the spectral similarity between *Grindelia* and *Salicornia* and the small patch size of *Grindelia*.

Artigas and Yang (2005) conducted a study to characterize the plant vigour gradient using hyperspectral remote sensing with field-collected seasonal reflectance spectra of marsh species in a fragmented coastal wetland. The data were acquired using Airborne Imaging Spectroradiometer for Applications (AISA), which was configured to 34 bands with 3.5–5.2 nm in bandwidth and 2.5 m in spatial resolution. The field measurements of spectra of marsh species were tested for their separability. The spectra of *Phragmites* in greening-up phases were used as the surrogate to determine the vigour gradient of common reed stands. They found that the spectra of one healthy stand of *Phragmites* sampled across the growing season provided equivalent signatures of pure physiognomic types, which can be used to determine the plant vigour gradient.

In addition to the above papers on hyperspectral remote sensing, Morris *et al.* (2005) assessed the distribution of relative elevations within a salt marsh landscape by integrating high-resolution imagery, Light Detection and Ranging (LIDAR) data and artificial neural network analysis. The relative elevation of the sediment surface within salt marsh land is regarded as a critical variable controlling the productivity of the salt marsh plant community. The study area, North Inlet estuary, is located along the south-eastern coast of the USA. The marsh landscape was classified by using neural network from a high-resolution image acquired by the Airborne Data Acquisition and Registration (ADAR) sensor. By using LIDAR elevation data covering the same area, the frequency distribution of marsh elevation relative to tidal elevations was computed. Their study suggests that shape of the frequency distribution of salt marsh elevations is diagnostic of stability and that the elevations of marshes imminently threatened by rising relative sea level would be focused at a lower limit of elevation for the vegetation.

There are some areas that need continuing research. Several authors addressed the fact that lack of ground data has been a major barrier in mapping wetland plant species from hyperspectral imagery. This has prompted the need to build comprehensive spectral libraries for different wetland plant species. Continuing research is also needed to develop efficient methods for determining the best endmembers, a core component in hyperpsectral data processing through spectral mixing techniques.

5. Landscape structure and pattern characterization

Watershed landscape characterization affects coastal water quality by altering sediment, chemical loads and watershed hydrology (Basnyat *et al.* 1999). Therefore, information on upstream landscape structure and pattern is indispensable for estuarine ecosystem assessment.

Characterization of landscape structure and pattern requires the use of land-use and land-cover data that are usually derived from remotely sensed data. The production of an accurate land-use and land-cover map is not a trivial task (Yang and Lo 2002). There are a variety of sources of remotely sensed data that can be used for land-use and land-cover mapping. But it is often difficult to find a cloud-free scene for a coastal area due to the high humidity. In Canada and northern Europe, radar products have frequently been used for land-use and land-cover mapping.

Mapping land use and land cover through an automated classification method has been challenged by the presence of complex urban impervious materials and agricultural lands, along with a variety of wetlands and vegetation covers, in coastal and estuarine environments. Identifying a method that can be used routinely is not easy (Campbell 2002). In this Special Issue, Yang and Liu (2005a) develop a method for land-use and land-cover mapping by using hierarchical classification and spatial reclassification. An image scene was separated into urban and rural regions early in the classification with a 'mask' defined by road intersection density slices combined with road buffers. Each part was classified independently in its most effective context and, later, both were merged to form a complete map. In spatial reclassification, image interpretation procedures, auxiliary vector data and a variety of GIS functions were synthesized to resolve spectral confusion and improve mapping accuracy. They used this method to produce a time series of land-use and land-cover maps from Landsat TM/ETM+ images for an estuarine watershed, with an overall classification errors of less than 10%.

As quantitative indices to describe landscape structure and pattern, landscape metrics can be computed from a classified land-use and land-cover map. They can be used to assess ecosystem health or as variables for models that support environmental assessment and planning efforts (Patil *et al.* 2001). With the development of GIS software technology, the measurement of landscape metrics seems to be unlimited and the choices of landscape metrics seem to be quite rich. However, many metrics may be partially or perfectly correlated with each other because they are actually derived from a few primary measurements that can be made from patches. Although recent studies indicate that landscape pattern can be characterized by using several independent core indicators, consensus has not been reached on the choice of individual metrics (McGarigal 2002). In this Special Issue, Yang and Liu (2005b) identify a method to select a set of core metrics in connection with a study aiming to characterize changing landscape pattern in an estuarine watershed. They computed an initial list of landscape metrics from the two classified land-use and land-cover maps for several different spatial observational units, including the entire watershed, four sub-watersheds and three predefined buffer areas. Then, they used landscape ecology principles, principal component analysis and Spearman's rank correlation analysis to eliminate redundant metrics. This resulted in a parsimonious set of core metrics which were not redundant but spanned the important dimensions of landscape structure and pattern.

Several areas need additional research. Continuing research is needed to develop improved methods for resolving the spectral confusion between different classes for middle-resolution imagery. There is an increased research demand to develop methods and technologies that can incorporate image spatial components as well as ancillary data for improving the classification of high-resolution image data. On the other hand, landscape pattern analysis with quantitative indices remains to be a challenge because of the inadequate understanding of the relationship between landscape pattern and ecological process and the technical difficulty in selecting the core metrics that can be used to characterize the health of an estuarine ecosystem.

6. Integrated assessment of an estuarine ecosystem

Integrated assessment of an estuarine ecosystem is needed to help understand the anthropogenic impacts upon an estuarine ecosystem. Many GIS datasets are available, which are related to biophysical and socio-economic conditions for different estuarine ecosystems. How can these data be integrated to assess the condition of an estuarine ecosystem? In this Special Issue, Host *et al.* (2005) describe a method for characterizing anthropogenic stressors in coastal ecosystems by integrating land-use and land-cover data derived from remotely sensed imagery with other GIS data such as population, road networks and point-source pollutants. With the use of such anthropogenic stress variables as proportion of agricultural or residential land use, population density, road density and distance to the nearest source, they classified aquatic habitats bordering the shoreline into a few ecological types through a watershed or a moving window approach. By using the magnitude of the most severe stressor, they further identified 'reference' areas that will serve as a benchmark for bioassessment and restoration efforts in coastal regions.

The ability to understand upstream anthropogenic effects upon downstream estuarine ecosystems is of great interest for coastal managers. This knowledge must be built upon an integrated approach that has been challenged by several issues concerning data integration and spatial modelling (Yang 2005). The first challenge is caused by the issue of data incompatibility. The data used normally come from very different sources. The incompatibility in parameter measuring and sampling methods has been a major barrier in data integration. The second challenge is related to the issue of information redundancy. Many initial environmental and social parameters considered may be highly or partially correlated and thus, information redundancy can be an issue. Continuing research is needed to develop methodology for reducing data redundancy so that a small number of independent core indicators can be identified. The last challenge is related to the design of an appropriate spatial observation unit so that both watershed and downstream conditions can be linked spatially. This is an area that has produced very little literature. It is actually a scale issue. Methodology for designing appropriate spatial observation units that fit different study sites needs to be developed.

7. Conclusions

Over the past few decades, remote sensing and GIS techniques have been increasingly used to support the environmental monitoring and assessment of estuarine ecosystems because of their cost-effectiveness and technological soundness. The combination of remote sensing and GIS forms a powerful framework for multi-scale spatial data acquisition and synthesis that are essential for characterizing the space–time continuum of a complex estuarine ecosystem. Nevertheless, estuarine ecosystems, because of their complex and highly dynamic landscapes, are challenging the applicability and robustness of these methods and technologies.

This article has reviewed the status of remote sensing and GIS applications in developing broad-scale environmental indicators for the assessment of an estuarine ecosystem. The emphasis was upon the contributions of this Special Issue that highlight the remote sensing and GIS research conducted by scientists primarily from the EPA EaGLe Program. Substantial progress has been made in four major areas – remote sensing of coastal water quality, submergent aquatic vegetation mapping, coastal marsh characterization, and watershed landscape pattern analysis.

Several major precedent areas were also identified for further research. They include the design of future ocean colour radiometers appropriate for shallow waters; the fundamental understanding of the functional linkage between water constituents and remote reflectance; the fundamental understanding of the relationship between the volumetric reflectance, SAV canopy density, water depth, and bottom reflectance parameters; the development of comprehensive spectral libraries for different wetland plant species in coastal and estuarine environments; the development of improved methods for resolving the spectral confusion between different land classes; and the fundamental understanding of the relationship between landscape pattern and ecological process.

Finally, an increased emphasis on integration in the assessment of an estuarine ecosystem has been highlighted because of the need for understanding the entire system as a whole and for understanding the linkage between upstream stressors and downstream responses. Several major challenges for integrated assessment of an estuarine ecosystem by using remote sensing and GIS have been identified, concerning the issues of data integration and spatial modelling.

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